System Studies and Simulations of Distributed Photovoltaics in Sweden

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Dissertation presented at Uppsala University to be publicly examined in Håggsalen, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Friday, December 10, 2010 at 13:15 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Grid-connected photovoltaic (PV) capacity is increasing worldwide, mainly due to extensive subsidy schemes for renewable electricity generation. A majority of newly installed systems are distributed small-scale systems located in distribution grids, often at residential customers. Recent developments suggest that such distributed PV generation (PV-DG) could gain more interest in Sweden in the near future. With prospects of decreasing system prices, an extensive integration does not seem impossible.

In this PhD thesis the opportunities for utilisation of on-site PV generation and the consequences of a widespread introduction are studied. The specific aims are to improve modelling of residential electricity demand to provide a basis for simulations, to study load matching and grid interaction of on-site PV and to add to the understanding of power system impacts.

Time-use data (TUD) provided a realistic basis for residential load modelling. Both a deterministic and a stochastic approach for generating different types of end-use profiles were developed. The models are capable of realistically reproducing important electric load properties such as diurnal and seasonal variations, short time-scale fluctuations and random load coincidence.

The load matching capability of residential on-site PV was found to be low by default but possible to improve to some extent by different measures. Net metering reduces the economic effects of the mismatch and has a decisive impact on the production value and on the system sizes that are reasonable to install for a small-scale producer.

Impacts of large-scale PV-DG on low-voltage (LV) grids and on the national power system were studied. Power flow studies showed that voltage rise in LV grids is not a limiting factor for integration of PV-DG. Variability and correlations with large-scale wind power were determined using a scenario for large-scale building-mounted PV. Profound impacts on the power system were found only for the most extreme scenarios.

Keywords: Photovoltaics, Solar energy, Distributed generation, Load modelling, Time-use data, Markov chain, Power flow, Power system

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I am too much i’ the sun.

Hamlet, Act I, Scene II
This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilization of energy, combined together in order to fulfill specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


IX Widén, J. (2010), Correlations between large-scale solar and wind power in a future scenario for Sweden. Submitted to *IEEE Transactions on Sustainable Energy*.


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**Other Publications**

XI Widén, J., Molin, A., Ellegård, K. (2010), Models of domestic occupancy, activities and energy use based on time-use data: deterministic and stochastic approaches with application to various building-related simulations. Accepted for publication in *Journal of Building Performance Simulation*.


Notes on my contribution

I am responsible for all model development, simulations and writing, except for:

*Paper I*, where I did the electric load modelling and half of the writing.

*Paper II*, where I did everything except the daylight modelling.

*Paper X*, where I did approximately half of the model development and simulations and most of the writing.
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<tr>
<td>CHP</td>
<td>Combined heat and power</td>
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<td>DG</td>
<td>Distributed generation</td>
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<td>DHW</td>
<td>Domestic hot water</td>
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<td>DSM</td>
<td>Demand side management</td>
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<td>GHG</td>
<td>Greenhouse gases</td>
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<td>GST</td>
<td>General Systems Theory</td>
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<td>LV</td>
<td>Low-voltage</td>
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<tr>
<td>MV</td>
<td>Middle-voltage</td>
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<tr>
<td>p.u.</td>
<td>Per-unit (fraction of a power system base unit, e.g. nominal voltage)</td>
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<td>PV</td>
<td>Photovoltaics</td>
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<td>PV-DG</td>
<td>Distributed photovoltaic generation</td>
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<td>TUD</td>
<td>Time-use data</td>
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<td>$W_p$</td>
<td>Watt-peak (indicates peak power of a photovoltaic module or array)</td>
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1. Introduction

During the first decade of the 21st century, the worldwide photovoltaic (PV) markets have experienced a tremendous expansion. In the IEA-PVPS countries—including the historically dominant PV markets of Germany and Japan—the installed PV power increased from below 1 GW to more than 13 GW between years 2000 and 2009 [1]. A majority of these systems are grid-connected and distributed, installed on buildings in low-voltage (LV) distribution grids. This expansion has been mainly due to generous subsidy schemes [2].

In Sweden the incentives for installing PV systems—which are still very expensive—have been few, although a number of actions have been taken over the past few years. There have been temporary subsidies for installations at public buildings [3] and currently a general investment support [4]. Moreover, with a crediting system for produced electricity such as net metering, these measures could further spark the development of a broader customer base for small-scale PV in Sweden. A continuation of these developments, in combination with prospects of decreasing prices for grid-connected PV systems, could make a more extensive integration of PV possible in Sweden in the future.

What would the consequences be of such a development? This thesis intends to answer some of the questions related to an expansion of distributed photovoltaic generation (PV-DG) in Sweden, and at high latitudes in general.

1.1 Aim of the Thesis

The work presented in this thesis is the outcome of a PhD project planned as an in-depth study of the implementation of small-scale energy technology. The questions that were posed related to the opportunities for, and consequences of, electricity end-users installing on-site generation with PV in the Swedish power system. For example, what would be the consequences for the distribution grid with a large number of connected PV systems? What would the value of solar electricity be for the end-users and how could it be given credit and be sold? How does utilisation of PV systems depend on the activities of the end-users?

This thesis deals with these questions, but also broadens the scope in terms of methodology and concepts. The study has three main aims, which are
answered by the appended papers:

1. **Improve modelling of residential electricity demand** (Papers I–III). Deterministic and stochastic electricity demand models that can be applied for studies of utilisation of on-site generation and distribution grid impacts were developed. The aim is to further develop, simplify and generalise the basis for residential load modelling. The models were developed in an interdisciplinary subproject, based on household activities, and can be applied in a number of contexts.

2. **Study the load matching and grid interaction of on-site photovoltaic generation** (Papers IV–VI). Utilisation of photovoltaic electricity in individual and larger aggregates of households was studied to answer some fundamental questions: Which is the stochastic interaction with the distribution grid? How well does the on-site generation match the local demand? How is the economic value of the production affected given different crediting systems, and which are the options for improvement?

3. **Add to the understanding of power system impacts** (Papers VII–X). The impacts on power systems from widespread and large-scale integration of distributed power sources are diverse and complex. The thesis contributes to the understanding by studying the impacts on voltage profiles in low-voltage distribution grids, the variability and smoothing effect in combinations of solar and wind power and the Swedish power system balance with a large-scale integration of solar and wind power.

The studies that the thesis is based on are system studies, in the sense that they treat the studied small-scale technology essentially as a black box that is introduced in larger systems: buildings, distribution grids and larger power systems. The methodology is based on modelling and simulations. The reason for this is that there are no examples of large-scale integration of PV systems in Sweden or at comparable high-latitude locations, and very few worldwide. Because of its importance this general methodology is given a short introduction in the next section. The subsequent section outlines the rest of the thesis and the appended papers are briefly summarised.

### 1.2 The Systems Approach

Concepts such as "systems thinking", "systems research", "systems theory" and "systems approach" are often associated with the so-called General Systems Theory (GST) that developed from the mid-twentieth century onwards. Systems theory developed from "operational research" during the Second World War. The American and British military engaged scientists
from various fields to approach strategic operations with scientific methods. This involved risk analysis, strategic planning and resource allocation [5]. From its very start, operational research also involved "asking stupid questions" [6] and questioning assumptions and solutions taken for granted by the military. The later development of GST combined operational research with Norbert Wiener’s cybernetics [7] and the more far-reaching ambitions of front-figure Ludwig von Bertalanffy [8]. The Society for General Systems Theory, formed in 1954, aimed at promoting the unity of science, increase communication between scientific areas and encourage transfer of ideas, models and approaches between disciplines [8].

1.2.1 What is a system?

According to a text-book definition a system is "a set of components that are united to a whole" [9]. A similar definition is that "a system is a set of parts coordinated to accomplish a set of goals" [6]. Kenneth Boulding, one of the front-figures of GST, uses a more general definition; a system is "anything that is not chaos" or "any structure that exhibits order and pattern" [10]. When defining a system, one has to decide what belongs to the controllable interior and what should be excluded to the fixed exterior. Drawing a border around a system is far from trivial, but there seem to be systems that are more or less easily delimited, while others are hard to define in a more fundamental way. In "The World as a Total System", Boulding makes an attempt at categorising different types of systems that can be perceived in the world [10]. The important questions regard their different degrees of complexity, how these systems interconnect and to what extent they are isolated. A summary of Boulding’s scheme is shown in Figure 1.1. These categorisations and denominations are of course possible to criticise; the point is the notion of different hierarchies of complexity where social systems score the highest.

1.2.2 System levels

The appearance of the web of patterns and structures that make up the world, in Boulding’s terms, changes with scale. Different aspects of a system are visible at different system levels. For example, on an astronomical scale the earth appears as a smooth geometrical object whose movement around the sun is accurately described by Newton’s laws of motion. Zooming in on the earth, mountains, valleys and plains appear as the roughness of the surface increases. Oceans at first appearing to be smooth surfaces exhibit waves and turbulent phenomena at close-up. The same applies to the scale of time. Different processes evolve on different time scales, e.g. societal development, biological evolution and geological processes. A systems approach is a revolt against the classical view of reductionism. Rather than having to be reduced to its parts, a system can be understood at different system levels but with dif-
Mechanical systems
Cybernetic systems
Positive feedback systems
Creodic systems
Reproductive systems
Demographic systems
Ecological systems
Evolutionary systems
Human systems
Social systems

Increasing complexity

Figure 1.1: Hierarchy of system types ordered by increasing complexity, after Boulding [10]. Cybernetic systems involve control through negative feedback. Most other category denominations are self-explaining.

Different descriptions. In the case of a gas, the movement of one gas molecule is unpredictable and can be described merely in probabilistic terms, whereas the combined behaviour of many gas molecules is uniform and possible to summarise in a deterministic law. This notion of the "stochastic nature" of the world, pronounced differently at different system levels, follows closely the foundations of Cybernetics [7, 8].

1.2.3 Modelling and simulation

To practically study a system, and to reproduce its performance, the perceived structure must often be further simplified. This is done by defining a model, which in itself is a system but chosen such that it "reproduces essential features of another system" [9]. The purpose of a model is to sort out important aspects of the perceived system or, conversely, to reduce unnecessary complexity [8]. When building a model, it is often possible to utilise the concept of 'structural similarity', i.e. that different phenomena exhibit systematic similarities and that they consequently can be described by similar models. When defining a model, the two considerations above must be taken into account. The system definition must be carefully made so that nothing important is excluded and nothing irrelevant is included. The level at which the system is studied must also be chosen with care, so that unnecessary complexity that can be reduced by 'zooming in' or 'zooming out' on the system. These issues become important in simulations of the system, which are reproductions of a system’s behaviour—one could say that experiments are carried out on the system model [9]—because they determine the complexity and computation time of the numerical operations involved.
1.3 Overview of the Thesis and the Appended Papers

The rest of the thesis is structured as follows. Section 2 gives a general background to the areas covered by the thesis and identifies the research gaps that motivate the different studies. Section 3 summarises the main theoretical and methodological concepts used in the appended papers. Sections 4–6 present the main results of the appended papers. Some final conclusions are drawn in Section 7.

The results of the thesis are based mainly on the appended papers:

• **Paper I** presents a method for converting time-use data (TUD) into load profiles for domestic hot water (DHW) and household electricity. The model is applied to a large Swedish TUD set containing sequences of daily activities for over 400 individuals. Validation against measured data shows that the model realistically reproduces hourly load patterns and can be used to estimate electricity and DHW use from reported everyday activities.

• **Paper II** presents a stochastic Markov-chain model for generating synthetic occupancy patterns with transition probabilities estimated from TUD. The occupancy patterns are used to model use of electric lighting in residential buildings. Validations show that the model reproduces important features of occupancy patterns and lighting demand, both in large populations and smaller sets of households.

• **Paper III** extends the Markov-chain approach to a nine-state model of the most important electricity-dependent household activities. The performance of the model is studied in detail and it is concluded that it captures the most important features of residential load profiles, including end-use composition, seasonal and diurnal variability, short time-scale fluctuations and random load coincidence.

• **Paper IV** studies the default load matching capability of on-site PV generation and how it can be improved by various measures. Out of the three studied options—PV array orientation, demand side management (DSM) and electricity storage—array orientation is the least impacting option and storage is naturally the most flexible. DSM has a non-negligible impact but depends on the flexibility of the demand profile.

• **Paper V** studies load matching and grid interaction of on-site PV in a number of Swedish households with a very detailed and high-resolved monitored electricity use. It is found that load profiles vary considerably between the households, which has impacts on how much electricity is used locally and how much is delivered to the grid. Explanations for the findings are determined from interviews with the households.


- **Paper VI** determines the effect of the mismatch between load and generation profiles on the production value of on-site PV generation. The impact of net metering, which reduces the mismatch as reported on the electricity bill, is studied. It is found that net metering has a considerable impact on the production value and on the system size that is reasonable to install.

- **Paper VII** analyses which time resolution is optimal for simulations of distribution grids with high penetration levels of PV-DG, using detailed monitored load and irradiation data. Time averaging reduces fluctuations in individual profiles but for simulated grid voltages the errors from using hourly averages are small and do not motivate using higher-resolution data.

- **Paper VIII** is a case study of three Swedish low-voltage distribution grids, modelled and simulated with different penetration levels of PV-DG. All studied PV systems are handled and voltage rise does not seem to be a limiting factor for PV-DG integration. However, systems around 1 kWp per household are most beneficial for reducing losses and improving voltage profiles locally in the grid.

- **Paper IX** studies different aspects of large-scale solar power variability. The correlation with large-scale wind power is studied, as well as the smoothing resulting from geographic dispersion. Combined solar and wind power is also studied. Although there is a combination that flattens the combined profile, hour-to-hour variability is always higher with a larger share of solar power.

- **Paper X** is an optimisation study of the Swedish power system under different conditions involving large-scale solar and wind power integration. Starting from today’s system, incremental amounts of solar and wind power are added. Addition of renewable power generation capacity affects electricity exports and imports, CO2 emissions and the use of fuels in the national district heating system.
2. Background and Previous Research

This chapter provides a general background to the main areas of research covered by the thesis. The need for an energy system transformation is discussed in Section 2.1. An overview of solar energy availability and technologies for utilisation of solar energy is given in Section 2.2, with a special emphasis on photovoltaics. Sections 2.3 and 2.4 give a background to the two main issues related to integration of photovoltaics: impacts of distributed and variable power generation in the power system. The chapter concludes in Section 2.5 with a summary of identified research gaps that the thesis aims to fill.

2.1 Towards a Transformed Energy System

From the mid-nineteenth century onwards the industrialised world has continuously increased the use of primary energy sources, mainly fossil fuels. Access to abundant, cheap fuels with high energy density has been a prerequisite and a driving force for the growth of modern society. Raised living standards, technological development and economical growth have thus become intrinsically linked to a non-sustainable harnessing of limited resources. The problems arising from this situation call for a transformation of the present energy system, involving both technology change and efficient energy use.

2.1.1 Problems and challenges

Figure 2.1 shows the development of primary energy use over the last 45 years in different parts of the world. Europe and North America have stood for the major proportions throughout the period. However, over the last decades there has been a marked increase in Asia and the Pacific, following economic growth in India and China. This development is expected to accelerate [11]. The current mix of primary resources is heavily dominated by fossil fuels, as shown in Figure 2.2. Oil, natural gas and coal together make up as much as 88 percent of the utilised resources.

The dominating use of fossil fuels is responsible for the two major challenges with the modern energy system. The first one is resource depletion. Fossil fuels are formed over long periods of time and even though new resource deposits may be discovered the consumption of the resources is much more rapid than the reproduction [13]. The question is not if but when ex-
Advocates of Peak Oil claim that the oil production is near or at its peak and that the world will experience accelerating decline rates of oil production in the near future [14]. Similar peaks will eventually occur for gas and coal, with challenges for resource supply and the whole global economy [13].

The second challenge is global warming, resulting from an amplification of the greenhouse effect due to increased concentrations of CO$_2$ and other greenhouse gases (GHG) in the atmosphere. The outcome of this development is highly uncertain. The Intergovernmental Panel on Climate Change, IPCC, predicts that the rise in global mean temperature over the 21st century will be below 1 °C from that of the period 1980-1999 if the CO$_2$ concentrations remain at the year 2000 levels, but possibly as high as above 6 °C with the worst scenario [15]. The predicted implications for the climate, ecosystems and society are profound, including sea level rise, freshwater scarcity, erosion, extreme weather events and resulting strains on world economy [15].

It is necessary to note that although resource depletion and climate change are the major challenges to energy systems around the globe, there are also other interferences in the natural subsystems on the earth that are linked to human processes in modern society. Rockström et al. [16] have proposed a set of so-called planetary boundaries that define a safe operating space for hu-
manity. Many natural systems and processes contain thresholds beyond which there might be disastrous consequences for humans. Climate change is one of nine such processes that are identified and one of three for which the safe boundary is already exceeded. The other two are loss of biodiversity and human interference with the nitrogen cycle. This suggests that the problem of human interference with nature’s systems is complex and cannot be limited to one single issue. On the positive side, the message is also that humanity can prosper and develop as long as the critical boundaries are not exceeded.

2.1.2 The need for a transition

It is generally agreed that a transition to a sustainable energy system is necessary for mitigating greenhouse gas emissions and decreasing the dependence on finite resources. According to the IEA, an "energy revolution" is needed [11]. IPCC concludes that a portfolio of technologies, including different energy conversion technologies and energy efficiency, has a high potential for mitigation and stabilisation of greenhouse gas emissions, but that "appropriate and effective" incentives have to be present for technology development, diffusion and deployment [15]. The Stern report, which was given much attention after its publication in late 2006, concludes that increased energy efficiency and a switch to carbon-neutral energy sources are necessary changes, but also that forcefully counteracting climate change in this way would be economically favourable for society compared to the negative economical impacts of an uncontrolled temperature rise [17].

The set of different emerging or mature low- or zero-carbon technologies for energy conversion that are often mentioned for climate change mitigation includes nuclear power, carbon capture and storage (CCS) and renewable energy technologies such as solar, wind, wave power or biomass. 'Low-carbon’, however, does not necessarily imply sustainability. CCS utilises a finite coal resource and would emit small amounts of CO$_2$. Nuclear power is dependent
on a supply of nuclear fuel and raises safety and waste issues. Biomass has the disadvantage of being a finite resource. Although there seems to be a consensus on the necessity of change, there is no ‘perfect fix’ that a transition should optimally include. However, a general conclusion is that a radical shift to a diversity of renewables in combination with energy efficiency is needed in the long run [11, 15, 17].

Some actions have already been taken. In order to decrease the GHG emissions worldwide the European community and other industrialised countries (with the notable exception of the United States) have ratified the Kyoto protocol, which sets binding targets for the participating parties to reduce of GHG emissions until 2012 by an average of 5 % as compared to 1990 levels [18]. The EU:s climate target is part of the union’s 2020 goals. The ambition is to reduce the GHG emissions by 20 % until 2020. This will be achieved by meeting the two other goals: reducing energy use by 20 % and increasing the share of renewable energy so that 20 % of the energy use is covered by renewables. The leaders of the respective EU countries have agreed to accept binding country-specific GHG reduction goals, with respect to the countries’ prerequisites, abilities and current achievements [19].

The EU has also implemented the EU Emissions Trading System (EU ETS) to help its member states meet their targets in the most cost-effective way. A proposal to strengthen this system has recently been presented. The most important changes are introducing an EU-wide emissions cap rather that national ones, as today, and that the cap will be tighter and successively decreasing [20].

2.1.3 The development of the Swedish energy system

The development of the Swedish energy system over the last 40 years is an example of profound system change. At the time of the oil crisis in the 1970s, most of the energy supply was based on oil. With the ambition to reduce the use and dependence on oil a number of changes were initiated. The most important were expansion of nuclear power and hydropower and an increased utilisation of biofuels. The use of crude oil and oil products has decreased with 45 % since 1970. Currently, nuclear power and hydropower make up the backbone of the electricity supply. Out of the 150 TWh electricity supplied in 2008, nuclear power and hydropower contributed with 64 and 69 TWh, respectively. Additional generation capacity is provided by combined heat and power (CHP) plants (8 TWh), industrial backpressure plants (6 TWh) and wind power (2 TWh) [21, 22].

The changes in supply have been accompanied by changes on the demand side. One way to decrease oil dependence was to promote the use of electric heating. The use of electric heating in the residential sector increased from below 5 TWh in 1970 to 29 TWh in 1990, when the increase levelled out. Currently, two thirds of Swedish detached single-family houses are heated
with electricity, while district heating is most common in multi-family build-
ings. Electricity for household electricity also increased, from 9 to almost 20
TWh between 1970 and 2008, due to an increased number of households and
increased appliance ownership [21].

The major current Swedish policy instruments for system change are energy
taxes on fossil fuels and electricity and green electricity certificates. The main
aim of the latter is to provide unbiased market-based support for increasing
electricity production from renewable energy sources and peat. Other instru-
ments are emissions trading and a programme for energy efficiency in the
industry sector [21].

2.2 Solar Energy and Photovoltaics

According to one definition, renewable energy is "energy obtained from the
repetitive currents of energy recurring in the natural environment" [23]. Solar
energy is not only one such resource—it is the ultimate source of most re-
newable energy forms available on the earth (exceptions include geothermal
heat and tidal energy resulting from the moon’s gravitational pull). Thus, us-
ing renewables is equal to using converted forms of solar energy, filtered or
stored in the natural processes of the earth. But why take the detour around
these? Would not a natural way of reaching sustainability be to utilise the sun
directly?

2.2.1 Solar energy and conversion technologies

The theoretical potential for direct utilisation of solar energy on the earth is
high in comparison to the current global energy use. The amount of solar
energy reaching the earth’s surface per year is around 10 000 times larger than
the roughly $10^5$ TWh of primary energy used per year [12]. The availability of
solar energy at a specific location on the earth depends on the movement of the
earth around the sun and its own axis and will thus exhibit annual and diurnal
variations. Climate, weather conditions and shading also affect the availability
of solar irradiation. In general, though, total availability of irradiation is not
primarily a limiting factor for future use of solar energy. For example, the
land area covered with photovoltaics required to meet all energy needs of a
country is, in many cases, less than the area used by the built environment [24].
Instead, effective and cost-efficient solutions for conversion and for handling
variability are the decisive factors [25].

Solar energy can be utilised directly in a number of ways. Solar collectors
absorb heat for hot water or space heating. Passive use of solar energy in
buildings provide to space heating and natural lighting. Solar-thermal power
plants use concentrated solar energy in steam-driven generators to produce
electricity. Finally, solar irradiance can be converted directly into electricity in solar cells.

**Figure 2.3:** An example of a photovoltaic array integrated in a window. Freiburg, Germany. Photo: J. Widén.

### 2.2.2 Photovoltaic technology and systems

The main component in a PV system is the photovoltaic array, made up of single solar cell *modules* (see Figure 2.3). When a solar cell is exposed to light, photons in the sunlight excite electrons in the semiconductor material (typically silicon) that makes up the cell. Due to material properties of the semiconductor the negatively charged electrons and the positively charged 'holes' that they leave behind are separated. This yields a voltage across the photovoltaic module, which makes it possible to get a current flowing through a connected load. Figure 2.4 shows schematically the function of a solar cell.

Solar cells are interconnected and collected in modules to raise the voltage and to provide protection and isolation. These modules, provided by manufacturers and retailers, are the building blocks of larger photovoltaic arrays. Just like single solar cells, modules can be connected in series and in parallel to raise the output power of the system. To maximise the collection of solar energy the orientation of the array has to be optimised. On the Northern hemisphere the array should face south and, for locations within 30° of the equator, have a tilt roughly equal to the latitude. For higher latitudes, lower tilt angles that favour summer production should be chosen because of the higher avail-
ability of energy during summer [26]. A photovoltaic system requires some additional equipment. For a stand-alone system a battery is needed to handle variations in energy availability. In grid-connected systems the array output is instead fed to an inverter that converts the dc output of the solar cells into ac for delivery to the grid when the system output exceeds the local load.

Solar cells can be used for various applications, from powering small pocket calculators to massive electricity production in large PV fields. The International Energy Agency’s research programme for photovoltaic technology, IEA-PVPS, defines four different types of systems: (a) off-grid domestic, (b) off-grid non-domestic, (c) grid-connected centralised and (d) grid-connected distributed [1]. The latter systems are typically installed on rooftops and facades of buildings. The main increase in total cumulative installed PV power in the IEA-PVPS participating countries has been for grid-connected systems. Although there is a lack of detailed statistics, most of these systems probably belong to category (d). The next section discusses this development.

2.2.3 Historical and current developments

Although the first solar cell for practical use was developed in 1954 [27], application of photovoltaic technology for energy conversion was for a long time restricted to very specialised areas such as the American space programmes. Except for some spiring interest during the oil crisis in the 1970s, it was not until the 1990s that markets for PV systems started to expand.

The major obstacle to a widespread application of PV is and has been high module prices. It becomes obvious that PV power generation needs financial
support and not only general market-based support such as CO$_2$ taxes and emissions trading if one considers the tax rates for fossil-based electricity that would be needed to make PV competitive. In 2005 it was estimated that the carbon tax rate required to reach the Kyoto protocol was 70 US$/ton C while a carbon price exceeding 1000 US$/ton C would be needed to make PV competitive [28]. Many countries have therefore introduced specific support for PV and other renewable power sources over the last decades.

The two countries with the historically largest PV markets and the highest installed power—Germany and Japan—are the ones that have had the most extensive subsidy schemes. In Germany the main support has been generous feed-in tariffs, resulting in a large increase in installed power and expanded markets during the last decade. In Japan the main subsidy has been an investment support, resulting in a close-to-autonomous market for solar cell applications [29]. Other countries have followed. The number of countries offering feed-in tariffs are three times as many as in 2005 [1]. The support schemes have had a marked impact on the creation and stimulation of markets for PV modules and system components, and for installed power. Since 1995, grid-connected power worldwide has consistently increased by more than 20 % per year, some years by more than 70 % [1]. The increasing trend for installed PV power is shown for later years in Figure 2.5. Note the boost in grid-connected power outside of Germany, Japan and the US between 2007 and 2008.

### 2.2.4 Solar energy and PV in Sweden

A common misconception is that total solar irradiation in Sweden, as well as in other high-latitude countries, is much lower than in countries that already have large amounts of PV installed (e.g. Germany) and that this would be
the main obstacle to a widespread use of PV. In fact, insolation in Sweden is only marginally lower than in Central Europe. Instead, the main challenge at high latitudes is the more pronounced annual variations with long days during summer and short days with a low solar altitude during winter [26].

Swedish market-deployment support for PV has thus far been limited to an investment support of 70% for installations on public buildings between 2005 and 2008 [3] and 60% for installations in general between 2009 and 2011 [4]. Although limited compared to subsidies in other countries the support has led to a series of projects that have gained attention and sharply increased the amount of grid-connected PV power in Sweden. Total cumulative installed power from grid-connected PV systems in Sweden was 3.5 MW in 2009. The major proportion of this power was installed between 2005 and 2009 [30]. This boost in grid-connected power can be seen in Figure 2.6, as well as the previous dominance of off-grid applications in Sweden. The small increase in centralised capacity is due to Sweden’s first centralised system in the Sala-Heby municipality [30].

![Figure 2.6: Historical development of installed power from different PV system categories in Sweden [30].](image)

However, lowering investment costs is only one side of the coin. Without receiving any credits for electricity delivered to the grid, it is still hard for larger grid-connected systems to pay back within a reasonable time. Following an inquiry on ways to facilitate grid-connection of distributed generation in Sweden [31] a legislative proposal for net metering of small-scale producers was expected, which would make it possible for customers to discount generated
electricity at the buying price, most likely with a billing period of one month. However, the possibility and consequences of net metering are now under pro-
longed investigation by the Swedish Energy Markets Inspectorate. As part of
the work presented in this thesis is linked to the investigation, more of this
will follow in subsequent chapters.

It should be noted that direct production-based support such as feed-in tar-
iffs is not likely to be introduced in Sweden. This form of support is normally
not considered compatible with the Swedish electricity certificates, which pro-
vide unbiased support to make sure that the most cost-effective technology is
supported. Yet, a form of feed-in tariff was established when the local power
company in the Sala-Heby municipality offered to buy electricity from the
local centralised PV system at a price higher than the market spot price [30].

Also in parallel to the development of public support, private initiatives
offering small-scale wind-power and PV systems for mounting on roof-tops
of detached houses or apartment balconies have emerged. For example, the
EgenEl initiative has gained much attention in the press, although it has pro-
vided to few installed systems at present [32, 33].

2.3 Distributed Generation

Large-scale integration of distributed PV systems would be a continuation of
two relatively new developments affecting the power system. On the one hand,
small-scale distributed PV systems installed at electricity end-users such as
residential buildings are examples of the general concept of distributed gen-
eration. This term is used to describe small generation units scattered in dis-
tribution systems. As will be discussed below, distributed generation alters
the traditionally unidirectional bulk flow of power in the power system, and
could have implications for design and operation of distribution systems. On
the other hand, large-scale variability would be introduced, which will be dis-
cussed in Section 2.4.

2.3.1 What is distributed generation?

Although local and small-scale generation are sometimes thought of as new
concepts, such solutions have been around since the early days of power de-
ivery. For example, the first wind turbines in Denmark, built by local en-
trepreneur Poul la Cour in the late 19th century, were relatively small-scale,
local, standalone solutions. These electrified windmills were meant to pro-
vide local power to develop the Danish countryside—much the same as the
aims behind contemporary electrification of rural areas in developing coun-
tries [34].

It is, rather, widespread introduction of small-scale generation in existing
power systems built for central generation and one-way supply of power that
is in some way novel—although such developments have been going on for several years. The early renewable power generators faced one major obstacle which made them infeasible for widespread use: variability, making it necessary to use local storage. Distributed generation handles variability by using the grid as a storage instead. One could therefore claim that widespread integration of small-scale renewable power generation in a way has benefited from and required the development of a large-scale grid infrastructure.

Many terms are used to describe application of small power generators scattered in the power system, although with somewhat different meanings. For example, 'dispersed generation' seems to refer to widely spread, very small systems, often owned by smaller end-use customers, while 'embedded generation' rather focuses on the production being embedded in the distribution grid structure. 'Distributed generation' seems to be a more general concept [35, 36]. There is yet no commonly agreed definition. Typical attempts at definitions require for example that the power generation is not centrally planned or centrally dispatched, normally smaller than 50–100 MW and usually connected to the distribution system [35]. A more concise definition is:

Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter [37].

The definition does not explicitly rule out any technology, and indeed there is a great variety of technologies suitable for DG. Combined heat and power (CHP) can, depending on size and connection, be counted as a form of distributed generation and is one of the most widely applied, especially in the Nordic countries [35]. Other examples include small-scale hydro plants, wind power plants and photovoltaics. Technologies that could become more widely applied in the future are fuel cells, flywheel storage units, micro-CHP and Stirling engines.

2.3.2 Impacts of distributed generation

The main reasons for installing distributed generation, as reported by policymakers, are reduction of CO₂ emissions through switching to renewable energy sources and obtaining diversity among energy sources [35]. Renewable energy technologies suited for DG, such as wind power and in particular PV, have no distinct economy of scale, which makes smaller units more feasible and decrease the size of individual investments. A larger share of renewables in the power system is therefore likely to imply more distributed generation.

A major benefit of DG is that it is located closer to the customers. This avoids transmission and distribution costs for utilities and grid companies. Although generation costs may be higher with DG as compared to centralised generation, transmission and distribution costs may decrease so much that DG is on the whole cost-effective for a utility [36]. Technological benefits with
distribution grid and the possibility of reduced voltage drops to customers.

Figure 2.7 shows, in principle, the impact of DG on distribution grids. The figure shows an idealised distribution feeder with 10 connected loads. At a high-load situation there is a considerable voltage drop along the feeder. This voltage drop, a design limit for distribution grids, increases with the length and resistance of the feeder. Managing the voltage level is important for not causing damage to equipment and reducing network losses. When DG is added at the end of the feeder the voltage drop is partially reduced, which is beneficial. At a low-load situation, however, the voltage drop is minimal by default and addition of the same amount of DG leads to an above-nominal voltage rise instead. If there is a massive excess DG production, upper voltage limits could be violated.

![Figure 2.7: Example of DG impacts on an idealised distribution feeder.](image)

Distribution transformer tap-changing mechanisms may further limit the amount of distributed generation by boosting the voltage at the secondary side of the transformer [35]. Depending on the DG technology, the generation unit may supply or absorb reactive power from the grid, which has impacts on losses and voltage profiles [35]. To sum up, grid topology, cable impedances, transformer control and placement and operation characteristics of DG in the grid all influence the resulting voltage levels. Although sometimes described as a limiting factor for DG, voltage management is rather a design problem and a matter of economy. However, one important question in the sense of a
limit is how much DG can be added to an existing grid before some kind of action has to be taken to manage the grid voltages.

Some other issues of DG are [35, 38]:

Power quality. Electronic conversion from dc to ac may produce currents that are not perfectly sinusoidal. This may have a negative impact on loads connected to the grid.

Reliability. Distribution grids are often radially fed, while grids on higher voltage levels have redundant interconnections to maintain power supply in case of faults. More DG in distribution grids would cause generation capacity to be increasingly unavailable.

Protection. When parts of a distribution grid are under maintenance, individual feeders are disconnected. This is not complicated if power is supplied from one point. With DG potentially injecting power from several points protection is more problematic and requires generators to automatically detect outages.

2.3.3 The importance of the end-user demand profile

As the example above has shown, grid impacts are distinctly different at low-load and high-load situations. In reality, the occurrence of these situations and the impact of DG depend on the demand profile and its coincidence with the often variable production. For studies and design of grids with DG, realistic and, especially for studies of smaller grids and local grid impacts, detailed load data are important. However, access to detailed load data is not obvious, especially not if they are to allow details on different end-uses.

Intuitively, measurements seem to be the obvious way to collect quantitative information about domestic energy use. Indeed, measurements of total domestic electricity use in individual households can be obtained rather easily, but to determine the proportions of different end-uses, specific measurement devices have to be installed. Consequently, most quantitative studies of domestic electricity study total electricity demand (see for example [39, 40]). However, following the development of policies towards increased energy efficiency there has been an increased interest for more detailed data about what people actually use electricity for. A number of large-scale surveys with end-use-specific measurements are performed in Europe [41] and there are examples from other parts of the world as well [42]. To improve the end-use statistics in Sweden, the Swedish Energy Agency initiated an extensive survey of energy use in the built environment in 2003 that was finished in 2008 [43, 44]. The aim has been to increase knowledge and statistics about energy use in households and premises, including electricity as well as cold and hot water. In a domestic electricity survey, power demand was recorded with 10-minute averages at appliance level in 400 households, both detached houses and apartments. The costs of such surveys are substantial, as well as the amount of data that have to be checked and analysed.
Load modelling should be a viable alternative, considering the drawbacks mentioned above. As discussed in [45], electricity demand models can be classified based on their resolution in space and time. Most available models are either based on a high time resolution or on a high spatial resolution, while resolution in the other dimension is low. Examples of models with low time resolution and high spatial resolution include econometric models, e.g. where annual demand is split up on different end-use categories. Examples of the converse are load forecast models where time-resolved power demand is modelled for an aggregate load at utility level.

An approach that goes beyond this classification is bottom-up modelling, where time-resolved power demand is built up step by step from basic components and can be aggregated for an arbitrary number of households. An often cited bottom-up model is the one by Capasso et al. [46], where load curves are constructed from power demand profiles of single appliances. Detailed data on demography, socio-economical status and lifestyle from a variety of sources are used. Another bottom-up model by Paatero and Lund [47] uses statistical mean values and general statistical distributions, which decreases the amount of data needed. Still, the problem with models having both high temporal and spatial resolutions is the amount of input data needed and the often complicated model structure. This is also the case with the very detailed high-resolution demand model presented by Stokes [48, 49]. The Stokes model, which is probably the most detailed domestic demand model up to date, is mainly derived from measured demand data series. Such approaches exclude the end-users as variable components in the model. There is a need for more general and more realistic model structures in which the demand is based on activities in households rather than the resulting power demand. A major challenge for such further demand modelling must be not only to make detailed models but to do it with the lowest possible complexity and need of input data.

2.3.4 Photovoltaics as distributed generation

Of the available technologies for distributed generation, PV is perhaps the one that is most suited for DG operation on a smaller scale. It is modular with no significant economy of scale, which makes centralised power plants insignificantly more cost-effective. Even more importantly, it is naturally suited for mounting on rooftops or walls of buildings or even integrated into building materials (cf. Figure 2.3).

Results from monitoring of a few residential areas with high penetration levels of distributed photovoltaics (PV-DG) are available from the PV-UPSCALE project [50]. The study covers four sites in Germany, The Netherlands and France. All sites have large amounts of PV-DG installed compared to what is normally the case in Europe. The per-household installed peak power varies between 1.5 and 3.2 kW_p calculated over all households in the respective area and between 2.9 and 6.3 kW_p calculated
over PV residences only. It was found that all power quality requirements in the European standard were satisfied and that the permissible PV capacity connected to a single LV feeder was relatively high, up to about 7 kW per household. Limits to the penetration level were not set by voltage rise along LV feeders due to excess generation, but rather by the rating of the distribution transformers, which limits the possible amount of reverse power flow through the transformer.

Experiences from high-density PV areas are also reported from the IEA-PVPS Task 10 [51, 52]. The survey covers a large number of areas around the world. At most locations, no negative impacts of PV-DG were reported. However, the studied communities had involved grid operators early on in the development and planning process, which made sure that many of the grids were designed to take large amounts of excess generation. Although no problems have been reported with these densities of PV-DG, there is still a need for studies of more types of areas at other locations and for even larger PV densities to confirm these particular findings. In particular, this is important when retrofitting PV-DG into existing grids rather than planning completely new PV-DG areas. For planning and estimating the impacts, simulations have to be performed.

Simulations of distribution grids with DG are often performed with static worst cases. In the worst-case approach, low-load and high-load events are treated separately to find extreme impacts on the distribution grid, much as outlined in Section 2.3.2. It is often a simple but revealing method if the extreme limits to the delivered voltage are the primary interest, for example in planning of distribution grids. It does not require detailed data series of demand and generation, only that estimates of extreme values can be done. One example of a static worst-case study of PV-DG is Povlsen’s study of limits to PV penetration in LV and middle-voltage (MV) grids [53]. The main conclusions are that the severe limits are posed at low-load situations, but also that these limits depend heavily on the actual magnitude of the load and on how close to the voltage limits the grid is operated.

A drawback with worst-case studies is that they do not show the diversity of impacts between the studied extreme values. For example, they do not tell how often overvoltages occur in different network nodes or how voltages or losses vary with fluctuations in demand and on-site generation. To capture these effects a stochastic approach is required, that takes regular and random variations into account. Conti and Raiti [54] address this problem and present a Monte Carlo method for probabilistic power flow in LV grids. It is concluded that a stochastic approach gives a better estimate of the impact of PV-DG on the network voltages and that many other aspects than extreme values can be determined, for example hours with over- and undervoltages. A variant of the stochastic approach is to create realistic series of demand and generation data for power-flow calculations. This is done by Paatero and Lund [55] for MV
2.3.5 Previous research in Sweden

PV-DG has thus far been studied relatively little in Sweden, reflecting the situation for subsidies and application of PV. The only more substantial system study is the report by Carlstedt et al. [57] that investigates the benefits with PV-DG for different actors, including utilities, grid operators and residential customers. The overall conclusion is that PV will be of most interest to residential customers, who will experience the highest value for on-site generated PV electricity, as it assumes the same price as bought electricity.

Grid issues are discussed in the report, based on simulations in [58]. Apart from a worst-case analysis, the simulations also include Monte-Carlo simulations based on Swedish data. With this analysis, 5 kWp systems installed at every household were deemed most beneficial from the grid point-of-view, although the maximum load of the customers was only half of that. The interpretation in the report is that PV system sizes twice as high as the maximum load per household could be allowed and be beneficial for grid operation. The methodology is questionable, partly because the analysis is based on the national Swedish demand, which is vastly more evenly distributed over the day than the residential demand is, partly because negative annual and diurnal correlations between demand and generation do not seem to have been taken properly into account. This is discussed in more detail in a comparison to the results of the thesis in Section 6.1.3.

The above discussion suggests that there is room for more detailed simulations of PV-DG in Sweden. Carlstedt et al. mention further stochastic modelling as a means to determine annual fluctuations in grid impacts. This is particularly interesting for high-latitude locations like Sweden, where the variations in solar irradiance are more pronounced than at lower latitudes.

2.4 Is Variability a Challenge?

Variability\(^1\) is an important feature of the major renewable power sources: solar power, wind power, wave power as well as tidal energy. It is probably also the most discussed and controversial feature, often described as a major obstacle to widespread and large-scale integration of renewables. The main issues of variability are discussed below.

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\(^1\)Intermittency is sometimes used synonymously with variability. Intermittency is however more suitable for describing unexpected shutdowns in conventional generation capacity while variability better describes output variations that are not due to faults but quite natural fluctuations in the renewable energy flows.
2.4.1 Typical variability in renewable power sources

The output from renewable energy sources typically varies characteristically over time. However, the nature of these variations differs between the energy sources. For photovoltaics the main variability is consistent seasonal and diurnal fluctuations due to the earth’s movement around its own axis and around the sun. This motion can be calculated very precisely (see Section 3.1). It also depends on the location. For example, at the equator the sun rises and sets at approximately the same time of day and describes the same path across the sky, while at high latitudes the day is longer in summer and the solar altitude higher than in winter. The occurrence of peaks also depends on the orientation of the photovoltaic array. With the tilt that maximises annual collection of solar energy at high latitudes the sun faces the array directly in spring and autumn rather than in the summer. Consequently, this is also when the highest output peaks occur [26].

The second source of variability is the weather conditions. Sunlight is attenuated in different ways before reaching the earth’s surface, mainly from scattering by molecules and particles and absorption by gases in the atmosphere. Around 30% of the sunlight is attenuated in this way [24]. Scattering also divides the sunlight into two distinctly different parts: one direct and one diffuse component. On a clear day, as much as 20% of the radiation on a horizontal surface may be diffuse [24], while on heavily cloudy days all radiation may be diffuse. On days with moving clouds direct radiation is recurrently cut off and consequently the output from a photovoltaic array can exhibit many peaks and troughs. Figure 2.8 shows an example of the variability in solar irradiance.

\[\text{Figure 2.8: An example of the variability in solar irradiance. 2-min resolution global irradiance data measured in a plane tilted 45° at the Ångström Laboratory, Uppsala, Sweden, during 4 days in June 2007.}\]
Other renewable energy sources have other types and sources of variability. For wind power, variations follow local wind speeds caused by moving weather fronts and specific local conditions determined e.g. by geographical factors such as mountain ranges and coastlines. In contrast to solar power, there is no underlying systematic variability, but the fluctuations are normally on longer time scales [59, 60]. Wave power variability is less well-known, but depends on both local and distant weather conditions [60]. Tidal energy is the most predictable type of variable power source. Two predictable blocks of energy occur each day, following the lunar cycle [60].

One important factor affecting variability is smoothing of the aggregate output from several individual and geographically spread renewable power generators. This is a well-researched phenomenon for wind power [61, 62, 63]. Many different studies have come to the same conclusion: geographic dispersion decreases the variations and increases the availability. For example, an American study found that as few as eight different sites were enough to eliminate the probability for zero wind power availability [64]. One of the largest studies made is Holttinen’s work covering the Nordic countries [61]. For solar power, the smoothing effect has not been subject to as many investigations, although some studies of reduction of weather-induced variability have been performed [65, 66].

2.4.2 Impacts on power systems

The impacts of variability on power systems are different depending on which system level is considered. For individual buildings variable production may mismatch the local demand, depending on the system size. This has implications for the end-user’s economy depending on the crediting system for energy supplied to the grid. There is also a recurrent exchange with the distribution grid in both directions. For individual systems the effect on the power system is marginal, but in areas with large penetrations, distributed generation becomes influential on the total production-load balance and on the voltage profiles in the local grid, as discussed above. In this case, variability has implications for local voltage management in the power system.

On higher system levels, such as regional or national, variable generation has a number of impacts. Variable production from hour to hour affects scheduling of other generation units in the system and transmission between geographical areas [67]. However, as power generation is planned hour by hour from predictions of supply needs, it is the unexpected deviations from planned generation that have to be handled. And, more importantly, as a power system may contain a number of variable and intermittent components such as generation units and loads, it is not uncertainty in one variable generation unit that is important, but the combined uncertainty in variable production, demand and conventional generation [68]. Power
systems have a number of ways to deal with such unexpected changes in the demand-production balance.

*Primary reserves* are automatically and instantaneously activated whenever the system frequency drops due to an imbalance between production and demand in the system. Primary reserves restore the balance but not the frequency drop. *Secondary reserves* are activated, often manually, on a slower time scale to raise the frequency and to replace the primary reserve capacity activated. Variable production on a large scale does put increased requirements on these system reserves, but not on a one-to-one basis. That is, an increase in variable generation capacity does not require an equal increase in reserves. For example, some estimates of the extra reserve capacity suggest that when wind power penetrates 10 % of the electricity demand, additional reserve capacity is 3–6 % of rated wind power capacity; for 20 % penetration the extra capacity is 4–8 per cent [68]. For the Nordic countries, Holttinen estimated the increased reserves to 2 % of wind power capacity at a 10 % demand penetration of wind power [61].

All new power generation units, including variable ones, increase total generation capacity and generated volumes. An important consideration is if the generation capacity is available when it is needed the most. Many previous studies have focused on the *capacity credit* of renewables, mainly wind power [62, 60]. The capacity credit is the ability of a generation plant to contribute to the peak demand and reliability of a power system. Normally, it is defined as the amount of conventional generation capacity that can be replaced by a certain amount of variable power while maintaining the same security of supply [62, 60]. A common result is that displaced capacity equals the mean wind power production for low penetration levels and decreases for higher penetrations [69]. For high penetrations the capacity credit is determined by the loss-of-load probability without wind power and the probability of zero wind power [62].

### 2.5 Identified Research Gaps

The discussion above has mentioned some examples of areas within the study of distributed photovoltaics where there is a lack of knowledge or where certain approaches can be improved. This section lists and summarises these areas and indicates how the gaps are filled by the appended papers. These areas are:

- *High-latitude conditions*. As already discussed, there is a lack of studies of PV-DG for Swedish conditions, and for high-latitude locations in general. There has been some research on photovoltaic systems in cold climates, but mainly for stand-alone systems. Both PV generation and demand have characteristics that are typical for high-latitude locations. In particular, the
pronounced seasonal variability of solar irradiance at high latitudes and the implications for grid-connected systems, distribution grids and power systems have to be further investigated. The specific variability and other features of high latitudes are considered in all appended papers.

- **Demand modelling.** As indicated, realistic studies of load matching and grid impacts of PV-DG require detailed load data. It is clear from the previous discussion that methods for modelling and generating such data have been developed previously. Apart from adapting a model for Swedish conditions, there are a number of theoretical issues involved that could be improved. First, load modelling would benefit from development of a transparent and simple model structure, as existing models tend to be complicated. Second, if the models were based on more general data, rather than being adapted to a mix of very specific data, they would be easier to adjust and apply for different purposes, also besides the applications in this thesis. Papers I–III present an approach for creating such a model.

- **Load matching and grid interaction.** The degree of load matching is crucial for a stand-alone PV system, but is not as often considered important for a grid-connected system. However, as long as sold electricity from on-site generation receives a lower credit than purchased electricity (as it does by default) it is more beneficial to use the generated electricity locally. Increased load matching also lowers the load on distribution grids. As is clear, not least from the investigations and debates on net metering in Sweden, there is a lack of knowledge about the mismatch between PV generation and typical residential demand profiles—how it varies between end-users, how it depends on the end-users’ activities, how and if it can be improved, and the implications for the end-user of different crediting alternatives for on-site generation. These questions are addressed in Papers IV–VI.

- **Distribution grid impacts.** As discussed, there is a need for studies on Swedish and high-latitude conditions concerning grid impacts. More generally, there are also gaps to be filled in terms of the scope and level of detail of such studies. For example, Paatero and Lund [55] only studied typical MV grids and not the voltage profile at final customers in real grid structures. In contrast, Thomson and Infield [56] studied real MV and LV grids combined, but for a limited period of time. Paper VIII fills this gap by simulating empirical Swedish LV grids, down to individual end-users over one year, so that all diurnal and seasonal variability is taken into account. For this type of studies, an important consideration is also the time resolution. Although previous studies on the effect of time averaging exist for individual demand and generation data series [70, 71], it is not
clear what the implications for grid studies are. Paper VII deals with this issue.

- **Power system impacts.** As indicated by the previous discussion, the question of power system impacts from variable production is vastly complex. This thesis does not attempt to make any full account of the impacts on the power system level, but considers two important aspects that have not been studied in detail previously. Many studies have considered variability and smoothing of individual power sources, but not so much different combinations. As wind power will already be integrated in Sweden and other parts of Europe when (or if) solar power enters the system on a large scale, it is important to study the variability in combinations of the two. Paper IX intends to fill this gap. Also discussed above, many previous studies have assessed the capacity credit of wind power. Solar power at high latitudes, in contrast, can be assumed to have no capacity credit, or a very small one compared to the annually generated volumes because of the mismatch with peak power requirements. For hydropower-dominated systems, which are energy-limited rather than power-limited, the capacity credit is less interesting. The important aspect is instead how addition of generated volumes, rather than capacity, affect scheduling of other generation units and affects the total system balance. This is studied in Paper X.
3. Theory and Methodology

The main body of research presented in this thesis is based on a simulation framework that contains models of incident solar radiation, daylight, photovoltaic systems, residential activities, load profiles and electric distribution grids, as well as some additional tools for simulation on higher system levels. Some of the models are based on standard approaches while some more innovative parts were developed in the research project. This chapter provides an overview of the conventional theoretical concepts behind the models, and some methods for evaluation and analysis.

Section 3.1 summarises the theory behind the solar energy models that are fundamental building-blocks of almost all the papers of the thesis. Section 3.2 reviews the theory behind Markov chains, which the stochastic demand models developed in the project are based on. A brief summary of the theory and computations needed for determining the power flow in an electric grid is provided in Section 3.3. Finally, Section 3.4 gives a brief overview of optimisation problems and how they are treated in some of the papers of the thesis. Section 3.5 summarises the analyses made on time series of power production and demand data to determine load matching and correlations.

3.1 Solar Energy Modelling and Simulations

The models described in this section were implemented for determining the solar energy incident on an arbitrarily tilted plane and, from the in-plane energy, the daylight level and the power output from a photovoltaic system, when given a set of meteorological data and additional system parameters. These models are fundamental to the work reported in the thesis, as they provide the tools to simulate PV systems with different parameters and orientations. As the models are based on standard approaches, only a summary of the most important parts is given, while a full account is provided in [XVI] and the other specifically cited references.

One important aim with the models has been to simultaneously model daylight and PV system output from the same irradiance data. This makes sure that the daylight data, later used for modelling domestic lighting, are correlated to the output of the photovoltaic system. A complete flowchart of the models and the input data that are needed is outlined in Figure 3.1. To compute the PV system output, beam and diffuse radiation are fed into a trans-
position model that calculates radiation components on the tilted plane of a photovoltaic array. These components are fed into a conversion model that generates the PV system output. Additional data for this procedure are albedo values that influence ground-reflected radiation on the tilted surface and ambient temperature that affects the solar cells’ conversion efficiency. Computation of illuminance components on the tilted plane of a window involves calculation of horizontal illuminance components from beam and diffuse radiation components and in a second step transposition of these to a tilted plane. Additional data for the daylight model are surface dewpoint temperatures.

Figure 3.1: Flowchart of the implemented models for radiation transposition, daylight and photovoltaic system output.

3.1.1 Radiation computations
In the following we consider computations starting from diffuse radiation $I_d$ and beam radiation $I_b$ incident on the horizontal plane. Radiation data are normally given as hourly values over a longer time period, but as the computations are static in the sense that all time steps are independent, only one time step is considered in the following and the time step length is not specified.

Because their origin in the sky differ, beam and diffuse radiation $I_b$ and $I_d$ are treated in different ways when transposing them to a tilted plane. A third component describing radiation reflected from the surroundings is also added.
The global radiation on the tilted plane can thus be expressed as

\[ I_T = I_{bT} + I_{dT} + I_{gT} \] (3.1)

where \( I_{bT} \) and \( I_{dT} \) are the beam and diffuse radiation on the tilted plane, respectively, and \( I_{gT} \) is the ground-reflected radiation.

In order to calculate the beam radiation incident on a tilted plane, given the beam radiation on a horizontal plane, it is necessary to know the geometric relationships between the tilted and horizontal planes, and between the tilted plane and the sun, at any instant of time. A number of angles are used to define these relationships:

- \( \phi \), latitude of the location, north positive, \(-90^\circ \leq \phi \leq 90^\circ\)
- \( \delta \), declination of the sun, north positive \(-23.45^\circ \leq \delta \leq 23.45^\circ\)
- \( \beta \), tilt of the plane with respect to the horizontal, \(0^\circ \leq \beta \leq 180^\circ\)
- \( \gamma \), azimuth angle of the tilted plane, zero due south, west positive, \(-180^\circ \leq \gamma \leq 180^\circ\)
- \( \omega \), hour angle, the angular displacement of the sun relative to the local meridian, zero at noon, afternoon positive, \(-180^\circ \leq \omega \leq 180^\circ\)
- \( \theta \), angle of incidence, the angle between the normal to the tilted plane and the radiation on that surface, \(-180^\circ \leq \theta \leq 180^\circ\)

The hour angle is determined from the time of the day in solar time. The declination is a function of the day of the year \( n \) and is described by empirical relationships, e.g. given by [72].

The angle of incidence \( \theta \) is related to all the other angles according to the following equation:

\[
\cos \theta = \sin \delta \sin \phi \cos \beta \\
- \sin \delta \cos \phi \sin \beta \cos \gamma \\
+ \cos \delta \cos \phi \cos \beta \cos \omega \\
+ \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega \\
+ \cos \delta \sin \beta \sin \gamma \sin \omega \] (3.2)

For a horizontal plane, the plane tilt \( \beta = 0 \), and the above relationship is simplified accordingly. The resulting angle of incidence \( \theta_z \), called the zenith angle, satisfies

\[
\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \] (3.3)
Zenith angle, surface tilt and surface azimuth angle are shown together with latitude and local meridian in Figure 3.2.

\[ I_{bT} = R_b I_b \]  

where the geometric factor \( R_b \) is defined as the ratio of beam radiation on the tilted plane to beam radiation on the horizontal plane:

\[ R_b = \frac{I_{bT}}{I_b} = \frac{I_{bn} \cos \theta}{I_{bn} \cos \theta z} = \frac{\cos \theta}{\cos \theta z} \]  

where \( I_{bn} \) denotes the beam radiation on a plane perpendicular to the incident radiation. This conversion is only performed when the sun is above the horizon. Thus, \( R_b \) is defined as above on intervals where both \( \cos \theta > 0 \) and \( \cos \theta z > 0 \), and is zero otherwise.

The diffuse radiation component is normally considered to consist of three parts—isotropic diffuse, circumsolar diffuse and horizon brightening—that differ in their origin in the sky. The isotropic diffuse part is uniform from every direction, the circumsolar diffuse part is concentrated around the sun’s position in the sky and horizon brightening is concentrated near the horizon. Thus, the diffuse component of radiation on the tilted plane can be expressed
Different models have been formulated to describe diffuse radiation on the tilted plane. In the isotropic model, all diffuse radiation is considered isotropic. For the model described here, the so-called Hay and Davies model was chosen [72]. Besides treating part of the diffuse radiation as isotropic, it also models circumsolar radiation. More advanced models are available, like the Perez-Ineichen model [73], which in addition takes horizon brightening into account. As Reindl et al. [74] have shown, however, the Hay and Davies model performs similarly to other, more complex models, including the Perez-Ineichen model.

In the Hay and Davies model, diffuse radiation on the tilted surface is expressed as

\[ I_{dT} = I_{dT,iso} + I_{dT,cs} + I_{dT,hz} \]  

(3.6)

where

\[ I_{dT} = I_d \left[ (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) + A_i R_b \right] \]  

(3.7)

Thus, since \( I_0 \) is the incident radiation that would be theoretically possible if there was no atmosphere, \( A_i \) is the fraction of radiation that is preserved as beam radiation after it has passed through the atmosphere.

The third and last component of the total radiation on the tilted plane in Equation 3.1 is radiation reflected from the ground. In reality, numerous objects such as buildings, different ground materials, trees, etc., reflect incident radiation onto the tilted surface. A simplified but standard approach is to assume reflected radiation from one composite source, a horizontal, diffusely reflecting ground. The ground-reflected radiation on the tilted plane is then dependent only on the reflectance of the ground and the view factor to the ground of the tilted surface:

\[ I_{gT} = I \rho_g \left( \frac{1 - \cos \beta}{2} \right) \]  

(3.9)

where \( \rho_g \) is the ground reflectance and \( I = I_b + I_d \) is the global radiation on the horizontal plane.

The ground reflectance \( \rho_g \) depends on the surroundings. At high latitudes, a seasonal variation in ground reflectance is likely because of snow coverage in the winter.
3.1.2 Daylight

Conversion to daylight illuminance is based on the Perez model [75] that converts diffuse and beam radiation into their respective illuminance components using a semi-analytical model formulation. Four basic parameters are derived to parameterise the insolation conditions:

- The solar zenith angle, $\theta_z$, as derived in the previous section.

- The sky clearness:

  \[ \varepsilon = \frac{I_d + I_n}{1 + \kappa \theta_z^3} \]  
  \[ (3.10) \]

  where $I_n$ is the normal incidence beam radiation, derived e.g. by Iqbal [76], and $\kappa$ is a constant equal to 1.041 if $\theta_z$ is given in radians.

- The sky brightness:

  \[ \Delta = \frac{I_d m}{I_0} \]  
  \[ (3.11) \]

  where $m$ is the relative optical airmass, derived in [77].

- The atmospheric precipitable water content:

  \[ W = e^{0.07 T_d - 0.075} \]  
  \[ (3.12) \]

  where $T_d$ is the surface dew-point temperature.

These parameters are used in a general model formulation

\[ F(\varepsilon, \Delta, \theta_z, W) = a_i(\varepsilon) + b_i(\varepsilon)f(W) + c_i(\varepsilon)g(\theta_z) + d_i(\varepsilon)h(\Delta) \]  
\[ (3.13) \]

where $F$ is a function describing the illuminance component in question, $f$, $g$ and $h$ are analytical functions and the coefficients $a_i$, $b_i$, $c_i$ and $d_i$ are discrete functions assuming different values for eight separate $\varepsilon$ bins. The exact analytical functions, bin ranges and look-up tables for the discrete functions are given for the different illuminance components in [75].

Transposition models for conversion to illuminance components on a tilted plane are also given by Perez et al. [75]. However, transposition with the HDKR model [74], similar to the transposition model used for radiation components, gave reasonable results.
3.1.3 Photovoltaic system output

Photovoltaic conversion of incident light depends on the fraction of radiation absorbed by the solar cell. This fraction is in turn dependent on the incidence angle of the incoming radiation. As the incidence angle increases, less radiation is absorbed and at incidence angles higher than 60° a substantial part of the radiation is reflected. At normal incidence, the fraction of radiation absorbed by the cell is equal to the transmission-absorption product \((\tau\alpha)_n\). The angular dependence of this factor is described by the incidence angle modifier (IAM) \(K_{\tau\alpha}\), which is defined as the ratio of absorbed radiation at a certain incidence angle to the absorbed radiation at normal incidence:

\[
K_{\tau\alpha} = \frac{(\tau\alpha)}{(\tau\alpha)_n} \tag{3.14}
\]

While \((\tau\alpha)_n\) and \((\tau\alpha)\) are seldom known separately, \(K_{\tau\alpha}\) is easily determined from measurements, e.g. by King et al. [78]. The radiation components are modified by different IAMs depending on the effective incidence angle. This is described in more detail in [XVI].

The conversion efficiency of a photovoltaic module is typically measured at standard test conditions (STC), which are defined by a module temperature \(T_{c,STC} = 25\,^\circ\text{C}\) and incident radiation \(I_{STC} = 1000\,\text{W/m}^2\). Given a power output \(P_{STC}\) at these conditions, the reference efficiency is

\[
\eta_{STC} = \frac{P_{STC}}{A_m I_{STC}} \tag{3.15}
\]

where \(A_m\) is the module area.

The conversion efficiency is affected by the cell temperature, which in turn depends on the ambient temperature and the incident irradiance. For the model the following relationship can be derived [72, 79]:

\[
\eta_e = \eta_{STC} \left[ 1 - \mu \left( T_a - T_{c,STC} + I_T \frac{T_{c,NOCT} - T_{a,NOCT}}{I_{NOCT}} (1 - \eta_{STC}) \right) \right] \tag{3.16}
\]

where \(T_a\) is the ambient temperature and \(T_{c,NOCT}, \, T_{a,NOCT} = 20\,^\circ\text{C}\) and \(I_{NOCT} = 800\,\text{W/m}^2\) are cell temperature, ambient temperature and incident radiation at the so-called nominal operating cell temperature (NOCT).

The output of the PV system is then

\[
P = NA_m I_T \eta_e (1 - q_{add}) \eta_e \tag{3.17}
\]

where \(N\) is the number of modules in the photovoltaic array, \(q_{add}\) represents additional array losses and \(\eta_e\) is the efficiency of the inverter and other equipment.
3.1.4 Implementations

As the model has been under successive development over the course of the project, some parts have occasionally been formulated slightly differently. Deviations should be clear from the presentation in the specific papers. The version formulated here has been implemented in a Matlab [80] environment for flexible use in different scripts and extensions. Parts of it are currently also being implemented for public release in an ongoing project. Validation of this model shows that it is, in terms of accuracy, directly comparable to commercial models like PVsyst [81]. Figure 3.3 shows some comparisons.

Figure 3.3: Performance of a PV system modelled as described here and with the commercial tool PVsyst [81]. The upper figure shows the system output per month, the lower the effect of different loss mechanisms on the annual output. For an optimally oriented system with standard components located in Stockholm, Sweden. The same meteorological data were used in both simulations.

The main differences between the results are a somewhat lower summer production and higher winter production in the model than in PVsyst. This is probably because of the additional array losses in the model, which are modelled with a constant loss factor.
3.2 Markov-Chain Modelling

The stochastic residential load models described in Chapter 4 are based on non-homogeneous Markov chains. A Markov chain is a random or stochastic process that has a number of specific properties that make it widely used in different fields of applied mathematics. This section summarizes some general definitions and practical considerations.

3.2.1 Definitions

A Markov chain is a stochastic process in discrete time [82]. The basic idea is that the process occupies one of a number of different states in each discrete time step and that the transitions between these states take place with some specific probability. Importantly, these transitions are only dependent on which state the process currently occupies. A typical example of a Markov chain is a random walk among the set of integers, where a step in either direction (+1 or −1) occurs with equal probability.

Formally, in a Markov chain $X(t)$, one of a number of states $E_1, \ldots, E_N$ is occupied in every time step $t = k$. The probability that the process occupies a state $E_i$ at $t = k$ is

$$p_i(k) = P(X(k) = E_i) \tag{3.18}$$

As the process must occupy one of the states in each time step, $\sum p_i(k) = 1$. When going from time step $t = k$ to $t = k + 1$, the state of the process at $t = k + 1$ is determined by transition probabilities, defined as

$$p_{ij}(k+1) = P(X(k+1) = E_j | X(k) = E_i) \tag{3.19}$$

As mentioned above, the probability for occupation of a state is dependent only on the state in the previous time step in this definition, often referred to as the so-called Markov property.

In a homogeneous Markov chain, the transition probabilities are the same regardless of the actual time step, i.e.

$$p_{ij}(k) = p_{ij} \forall k, \tag{3.20}$$

whereas in a non-homogeneous Markov chain the transition probabilities change with time. The non-homogeneous version is useful for describing phenomena with, for example, systematic diurnal patterns. The result is an interesting mix of both random and more systematic variability.
It is possible to determine, in each time step, the aggregate behaviour of the stochastic process. With transition probabilities ordered in a transition matrix

\[
M(k) = \begin{pmatrix}
p_{11}(k) & \cdots & p_{1n}(k) \\
\vdots & \ddots & \vdots \\
p_{n1}(k) & \cdots & p_{nn}(k)
\end{pmatrix}
\] (3.21)

the theoretical distribution of occupied states is

\[
p(k) = (p_1(k) \ldots p_n(k)) = p(1) \prod_{\tau=1}^{k-1} M(\tau)
\] (3.22)

where \( p_i(k) = P(X(k) = E_i) \) is the probability for state occupancy in time step \( t = k \).

The existence of this set of probabilities makes it possible to theoretically determine the aggregate behaviour of the non-homogeneous process over time, when the number of individual realisations of the process approaches infinity. Thus, the combined behaviour of a large number of realisations is essentially deterministic whereas single realisations exhibit much more randomness. This will prove very useful for electrical load modelling, as discussed further in Chapter 4.

### 3.2.2 Estimation of transition probabilities

When empirical data are available that can be interpreted as (at least approximate) realisations of the Markov chain process, it is quite straightforward to estimate the transition probabilities from these. Suppose that we have a series of data \( s_i(k), i = 1, \ldots, N_s, k = 1, \ldots, N_t \). Between time steps \( k \) and \( k+1 \), all \( N_s \) transitions \( s_i(k) \) to \( s_i(k+1) \) are examined and the total number \( n_{ij}(k) \) of transitions between states \( i \) and \( j \) are counted. The total number of transitions from state \( i \) is then \( n_i(k) = \sum_{j=1}^{N_s} n_{ij}(k) \), and the transition probability estimate is:

\[
p_{ij}(k) = \frac{n_{ij}(k)}{n_i(k)}
\] (3.23)

If not all states have transitions from them in every time step, \( n_i(k) \) will be zero, which is problematic since \( n_i(k) \) is in the denominator. One solution is to divide the time series into intervals of a number of time steps and calculate average transition probabilities over these intervals:

\[
p_{ij}(k) = \frac{\sum_{\tau=a}^{b} n_{ij}(\tau)}{\sum_{\tau=a}^{b} n_i(\tau)}
\] (3.24)

for \( k \in [a, b] \).
3.2.3 Markov chain realisation

Simulation, or realisation, of a Markov chain is done by generating a uniform random number in each time step on the interval \([0, 1]\). This number is then compared to the set of transition probabilities, ordered on the same interval, as outlined in Figure 3.4.

![Figure 3.4: Schematic outline of a realisation of a Markov chain.](image)

3.3 Power Flow Computations

Studies of the power flow in a power transmission or distribution grid are important in planning, design and operation of power systems. For the subject of this thesis, integration of photovoltaic power generation in distribution grids, power-flow studies make it possible to determine how the grids react to different integration levels of distributed generation in terms of line flows, bus voltages and losses. This section covers briefly how these calculations are performed.
3.3.1 Setting up the equations

We consider the power flows to and from a general grid bus $i$ in a grid with a total of $N$ buses, as shown in Figure 3.5. A load with active and reactive power $P_{Li}$ and $Q_{Li}$ and a generation unit injecting active and reactive power $P_{Gi}$ and $Q_{Gi}$ are connected to the bus. This means that a net active power $P_i$ and a net reactive power $Q_i$ enter the network at the bus. There are also connections to other grid buses. Each such line has a known admittance

$$Y_{ij} = |Y_{ij}| \angle \delta_{ij}$$

(3.25)

each bus has an unknown voltage

$$V_i = |V_i| \angle \theta_i$$

(3.26)

![Figure 3.5: Scheme of a generic grid bus in the power flow problem.](image)

From these definitions the power flow equations can be derived via Kirchhoff’s laws [83]. These equations relate the unknown voltage magnitudes and phase angles to the known parameters:

$$P_i = \sum_{n=1}^{N} |Y_{in}V_iV_n| \cos(\delta_{in} + \theta_n - \theta_i)$$

$$Q_i = -\sum_{n=1}^{N} |Y_{in}V_iV_n| \sin(\delta_{in} + \theta_n - \theta_i)$$

(3.27)

As can be seen there are two equations and two unknown variables for each bus (voltage magnitude and phase angle). One of the buses has to be designated as the system slack bus, with a specified voltage and an unconstrained supply (or reverse flow) of power to (or from) the grid.\(^1\) This leaves us with $2(N-1)$ equations and as many unknowns. To find the solution to the power flow problem, this set of nonlinear equations must be solved.

---

\(^1\)Although not considered here, other buses can also be voltage-controlled, resulting in further reduction of unknown variables and equations.
3.3.2 Solving the power flow problem

Newton’s method for solving nonlinear equation systems can be effectively applied to the power flow problem. The unknown voltages can then be found as the roots of the mismatch equations

\[
\Delta P_i = P_i - \sum_{n=1}^{N} |Y_{in}V_iV_n| \cos(\delta_{in} + \theta_n - \theta_i)
\]

\[
\Delta Q_i = Q_i + \sum_{n=1}^{N} |Y_{in}V_iV_n| \sin(\delta_{in} + \theta_n - \theta_i)
\]

(3.28)

Assuming that bus 1 is the system slack bus, the unknown bus voltages can be found by repeating the iterative scheme

\[
\begin{pmatrix}
\theta^{(k+1)} \\
|V|^{(k+1)}
\end{pmatrix}
= \begin{pmatrix}
\theta^{(k)} \\
|V|^{(k)}
\end{pmatrix}
- J^{-1}(\theta^{(k)}, |V|^{(k)})
\begin{pmatrix}
\Delta P(\theta^{(k)}, |V|^{(k)}) \\
\Delta Q(\theta^{(k)}, |V|^{(k)})
\end{pmatrix}
\]

(3.29)

where

\[
\begin{pmatrix}
\Delta P \\
\Delta Q
\end{pmatrix}
= \begin{pmatrix}
\Delta P_2 \\
\vdots \\
\Delta P_N \\
\Delta Q_2 \\
\vdots \\
\Delta Q_N
\end{pmatrix},
\begin{pmatrix}
\theta \\
|V|
\end{pmatrix}
= \begin{pmatrix}
\theta_2 \\
\vdots \\
\theta_N \\
|V_2| \\
\vdots \\
|V_N|
\end{pmatrix}
\]

(3.30)

and the Jacobian is

\[
J = \begin{pmatrix}
\frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\
\frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|}
\end{pmatrix}
\]

(3.31)

Starting from an initial guess \( \theta^{(0)}, |V|^{(0)} \) the iteration is repeated until the mismatches have reached a reasonable tolerance level.

For this thesis project, Newton’s method for power flow was implemented in Matlab [80], to allow flexible integration with the solar energy models described above.

3.4 Optimisation

In some of the papers an optimisation approach is used, for example to adjust the orientation of PV arrays to match a certain load profile or to schedule
the use of resources and power plants in the Swedish power system in the most effective way. An optimisation problem is solved by finding a set of parameters that maximise (or minimise) an objective function. As existing models and solvers for optimisation problems have been used in the project, details are left out and can be found in the cited references.

A typical non-linear optimisation problem considered in the thesis is:

\[
\min_{x} f(x) \text{ subject to } \nonumber \\
(g(x) \leq 0) \nonumber \\
h(x) = 0 \nonumber \\
l \leq x \leq u
\]

(3.32)

In cases where there are exclusively linear relations between the parameters and variables and the function \( f(x) \) is a linear combination of the elements of \( x \), the problem can be written as a linear programming problem (on standard form):

\[
\max c^T x \text{ subject to } \nonumber \\
Ax = b \nonumber \\
x \geq 0
\]

(3.33)

The energy system optimisation model MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) [84, 85], which is applied to optimise the Swedish power system operation and balance under different conditions (Section 6.2.3), formulates resource flows, conversion in power plants, demands and other constraints as a linear optimisation problem and uses linear programming to find the most cost-effective solution. MODEST is similar to other, widely used, energy system optimisation models such as MARKAL and EFOM [86, 87] but is more flexible. For example, it is based on a ’quasi-dynamical’ time division that allows, for example, periods with significant fluctuations in important variables to be modelled with a higher time resolution. MODEST has been applied previously to both local and national energy systems (see for example [84, 88, 89]).

3.5 Methods for Data Analysis

Some methods for analysis of modelled data are common for many of the studies included in the thesis. This section covers some general definitions.
3.5.1 Grid interaction and load matching

An important piece of analysis regards the interaction and overlap between two (often stochastic) data series, usually representing load and generation curves. This determines, for example, the amount of electricity saved locally in a building with on-site generation and the building’s interaction with the local distribution grid.

Considering two power data series \( P(k) \) and \( L(k) \), representing production and load at a time step \( k \), the net production and net load are

\[
\tilde{P}(k) = \max(0, P(k) - L(k)) \\
\tilde{L}(k) = \max(0, L(k) - P(k))
\]

The matching part, which for example could be the load covered by the production from a photovoltaic system, is

\[
P(k) - \tilde{P}(k) = L(k) - \tilde{L}(k)
\]

The load matching fraction over a given time interval or, in the case of photovoltaic electricity, the solar fraction can be defined as:

\[
SF = \frac{\sum_i (P(i) - \tilde{P}(i))}{\sum_i L(i)}
\]

3.5.2 Analysis of system states

In many cases a resulting data series representing the present state of a system—it may be, for example, the power supply from a generation unit or the voltage at a specific bus in a distribution grid—has to be analysed in a comprehensive way. One option is to draw a duration graph, which sorts the system states in decreasing order, see Figure 3.6. The information in the duration graph can alternatively be presented as a cumulative distribution function, which, for a given value, is defined as the probability that the system state is in fact below this value:

\[
F_X(x) = P(X \leq x)
\]

The relationship between the duration graph and the cumulative distribution function is shown in Figure 3.6.

3.5.3 Correlation analysis

To determine if two data series, for example the output from two power generators, follow the same pattern with respect to time, the degree of correlation can be determined. For two data series \( X(k) \) and \( Y(k) \), the correlation coeffi-
The correlation coefficient is defined as:

$$\rho_{X,Y} = \frac{\sum_i(X(i) - \bar{X})(Y(i) - \bar{Y})}{\sqrt{\sum_i(X(i) - \bar{X})^2} \sqrt{\sum_i(Y(i) - \bar{Y})^2}} \quad (3.38)$$

where

$$\bar{X} = \frac{1}{N} \sum_{k=1}^{N} X(k)$$

$$\bar{Y} = \frac{1}{N} \sum_{k=1}^{N} Y(k) \quad (3.39)$$

The correlation coefficient is equal to one when there is an exact correlation and equal to zero when the two data series are completely uncorrelated.
4. Demand Modelling

This chapter summarises the domestic demand models developed to realistically reproduce the electricity demand in residential buildings. A full account of the development, implementation and validation of the models is given in Papers I–III. The aim with these models is primarily to provide data for the load matching analyses and detailed distribution grid simulations in the thesis, but also to provide a general modelling framework for other similar purposes. Below, an introduction and a motivation to the basic approach behind the models is given in Section 4.1. Section 4.2 summarises the two basic model types and shows examples of the model performance. Finally, Section 4.3 lists some examples of applications and discusses a few issues for future development.

4.1 The Activity Approach

In general, energy use can be regarded as a function of three variables: the set of technological artifacts involved, the energy performance of these artifacts, and the use of them. While the first two are usually easy to determine and describe, the use of the technology is more complex (cf. the difference between mechanical and social systems in the hierarchy of system complexity in Figure 1.1). The basic idea of the demand models developed is to obtain a realistic description of the use patterns underlying and determining domestic energy demand.

4.1.1 The need for interdisciplinarity

Social aspects on domestic energy use have been extensively studied over the past decades. Many detailed research overviews have been presented previously, for example [90, 91, 92]. Early on in this project, a literature survey of more recent research, including both quantitative and qualitative studies, was made [XXIII]. The main conclusion from this research overview is that technical research and sociologically oriented research have traditionally been separated, both internationally and in Sweden. There is a need for more studies in the "borderland" between technological and social-scientific approaches. In the literature review by Lutzenhiser, it was concluded that there is a lack of efforts that tie people's activities and actions closer to the technical artifacts of everyday life. Lutzenhiser writes that the literature in the field "[...] has gen-
erally failed to connect, for example, the energy impacts of social action with with the physical performances of buildings, technologies, and the natural environment" [91]. A major reason for this has been difficulties to perform sociological studies in the technologically dominated energy research field [93]. Similar conclusions are drawn in other reviews. Ketola [90] concludes that research in Sweden has suffered from sporadic studies and bad coordination.

One problem has been that technologically oriented researchers on energy use and energy savings lack interest in, or are unaware of, the importance of the user and the reasons behind his or her energy use. As Elisabeth Shove puts it: "They are generally concerned with the end result, not the process" [94]. One example from Sweden that illustrates the impact of the end-user, in contrast to purely technological efficiency measures, is a survey of electricity end-use in 66 detached houses from 1994, which investigated the potential energy savings from switching to energy-efficient appliances [95]. The suggested savings now appear to have been counteracted by an increased overall use of appliances [96], something that was not and could not be foreseen in the technological survey.

Another problem is that there is a lack of quantification in sociologically oriented research about energy use and energy efficiency and, where there is quantification, a lack of generalisation. One reason could be, as Carlsson-Kanyama et al. [97] suggest for Sweden, that it is problematic to perform studies with statistical certainty because of a lack of general quantitative data and statistics, but also because of the complexity of the problem, which makes factors vary between studies. To improve quantification and generalisation, and to improve the interdisciplinarity of the research field, there is a need for studies and approaches that combine quantitative and qualitative methods [98].

4.1.2 Time use and time geography

The need for a combination of quantitative and qualitative approaches was the starting point for the load model development presented here, which is based on the time-geographic approach. Time geography was developed by Torsten Hägerstrand at Lund University, Sweden, and was presented by the end of the 1960's. It aims at providing a basis for analyses of phenomena where the basic dimensions time and space are central [99]. It also aims at bridging the gap between material processes and peoples' subjective experiences of these processes. In the time-geographical approach, individuals perform activities to satisfy their everyday needs through use of available resources. The possibility for this is delimited by restrictions created by social practices, organisational structures, distances between geographical locations and abundance and availability of resources [100].

Thus, in time geography, the view of individuals' everyday life as a sequence of movements or activities in space-time with an inherent logic is fundamental. A notation system has been developed for describing such pro-
cesses [101]. Examples of an individual path, which describes an individual’s movement between places over time, and an activity-oriented path, which simplifies the individual path into a sequence of activities, are shown in Figure 4.1.

![Figure 4.1](image)

Figure 4.1: Example of a time-geographic individual path (to the left) and a corresponding activity-oriented path (to the right). The activity-oriented path is a projection of the individual path on the time axis [XI].

Activity sequences can be empirically collected in the form of time-use data (TUD), usually with hand-written diaries in which individuals continuously note their activities. To arrive at a coherent definition of different activities and to make it practically possible to construct activity sequences from the diaries, an empirically-based categorisation scheme has been developed. The result is a hierarchic scheme where activities are defined on different levels of abstraction [100].

Time-use surveys have been conducted by Statistics Sweden at regular intervals, typically every tenth year. Results from time-use surveys in 1990/1991 and 2000/2001 have been summarised previously [102]. However, the most well-researched time-use data set originates from a pilot survey of time use in Swedish households from 1996. This is the data set that has been utilised for the model development in this thesis. The data, which have been presented in [103], contain TUD for complete households on one weekday and one weekend day, down to a one-minute resolution. In total, 463 individuals in 179 households, covering an age span from 10 to 97 years, participated. Although these TUD are more than a decade old, the scope and degree of detail are unsurpassed by subsequent studies, and there is no data set that has been as extensively tested for consistency and completeness.

It is clear that time geography and TUD should be excellent tools for describing and explaining the activities underlying energy demand patterns in households. They also have a great potential to meet the need for interdisci-
plenary energy-use studies, as they can bridge the gap between quantitative and qualitative studies.

4.1.3 Empirical connections between activities and load patterns

Empirical insight into the interplay between everyday activities and energy use can be obtained through detailed case studies of individual households. In a study connected to the Swedish Energy Agency’s measurement survey [43, 44], 14 households were studied closely, using a wide range of methods, including appliance-specific high-resolution measurements of domestic electricity, interviews with household members and time-use diaries. The results have been extensively reported in [XIX]. Although not included in the thesis, the study provided material that is used in different ways in many of the appended papers.

The main aim of the study was to find out how households reason about domestic electricity use, identify electricity-use patterns and activity patterns related to different functional areas—in particular those that indicate an increased appliance and electricity use—and determine how electricity-use patterns relate to energy efficiency. The main result was the identification of a number of basic activity patterns that involve direct use of energy. For example, one important result is the difference between individual and collective use, where appliances are used by one and by many persons, respectively. These patterns can be further divided into serial use, where the same appliance is used at different occasions, and parallel use, where two or more appliances are used at the same time. These, and other concepts, such as the notion of process time during which energy is used but no active person is involved, are important for revealing the logic in everyday activities, and are useful when modelling energy use in households. The study also involved feedback of measurement results to the participating households. The main information provided to the subset of households that wrote time diaries was activity profiles with associated power demand, which were effective in revealing which activities provide to energy use and to demand peaks.

Another important result from the study, and also a general conclusion in the whole measurement survey of the Swedish Energy Agency [96], is that electricity use varies considerably between households. Figure 4.2 shows measured annual electricity use for different end-use categories. Total electricity demand varies, as well as the proportions of different end-uses. These differences are to some extent correlated to household sizes and different appliance sets in the households, but also to the use patterns of household members. The study’s detailed measurements also revealed other characteristics of the load data that should be captured by a load model, including diurnal and annual variations, short time-scale fluctuations and load coincidence.
4.2 Overview of the Models

The model framework developed for determining load profiles from TUD includes a *deterministic* approach, where empirical activity sequences are converted into energy-use patterns, and a *stochastic* approach, where synthetic activity patterns are probabilistically generated and then converted into energy-use patterns. These approaches are summarised below, while more detailed descriptions can be found in the appended papers.

4.2.1 The deterministic approach

In Paper I, a conversion model for constructing load profiles for household electricity and domestic hot water (DHW) from TUD is presented and validated against measurements both on an aggregate population level and for individual households. The model is applied to the Swedish set of TUD from 1996 described above. In addition, the combined survey of electricity use and time use in the 14 case-study households allows a direct comparison between power demand modelled from TUD and actual measurements. Preliminary results from the whole measurement survey by the Swedish Energy Agency were also used for comparison with the aggregate modelled demand.

Construction of load profiles from TUD is done with a set of conversion functions, basically through connection of appliance or water-tap loads to
specific activities that correspond to different end-uses. In general, a constant power demand is either required during the activity or after the activity (‘process time’), with different time constraints. Modelling of lighting involves a varying power demand that is dependent on hourly daylight data. The method is described in detail in Paper I and for household electricity also in a separate report [XX]. An example of the model output is shown in Figure 4.3. It is clearly seen how the distribution of activities over time gives rise to a characteristic daily demand pattern and that the TUD determine how these activities are distributed across the studied population.

Comparisons with measurements show that the modelled load profiles are realistic both on an aggregate level and for individual households. The important result is that TUD yield a realistic spread of end uses over time and, consequently, that they can provide to energy-use studies and modelling of energy demand. TUD can act as a complement to measurements, giving additional information on individuals’ energy-demanding activities that measurements on household level could never provide. The study also suggests that modelling from TUD could be an alternative to end-use-specific measurements.

![Figure 4.3: Example of activity-to-power conversion in the model presented in Paper I.](image)

In this case, no standby power demand is included.

Figure 4.3: Example of activity-to-power conversion in the model presented in Paper I. The activity graph to the left shows activity patterns for the activity 'watching TV' with individuals ordered by increasing age from left to right. The graph to the right shows the aggregate power demand for TV modelled from the activity patterns.
4.2.2 The stochastic approach

The advantages of converting empirical activity sequences into load profiles is that the modelling can be very detailed, with the limit set by the degree of detail recorded in the time-use diaries. However, the approach requires access to an entire TUD set, and the model will have the same limitations (number of households and time span) as the original data set. In many applications longer data series are needed, as well as the possibility to generate activity sequences for an arbitrary number of households with different numbers of members. These were the main reasons for developing a stochastic model.

The stochastic approach, presented in Papers II and III, is based on a non-homogeneous Markov-chain model, as outlined in Section 3.2. Apparently, activity patterns in the form of TUD have properties that make them resemble realisations of Markov chain processes. In the model formulation, the states $E_1, \ldots, E_N$ correspond to different activities, and the transition probabilities $p_{ij}$ can be estimated from a TUD set with Equation 3.24. With this model, synthetic activity patterns can be generated as outlined in Figure 3.4, and conversion to load profiles can be done as in the deterministic model. In Papers II and III a set of somewhat more sophisticated conversion functions are used, in particular a lighting model using the daylight modelling described in Section 3.1.

The property described in Equation 3.22—the existence of a set of probabilities for state occupancy—makes sure that there is a well-defined aggregate behaviour when the number of load profiles is large. This means that with transition probabilities estimated from empirical TUD, the aggregate distribution of activities over time in a large set of realisations will reproduce that in the original TUD set. This also suggests that coincidence effects will be reproduced. For individual modelled households, the resulting profiles will be stochastically variable, while a more well-defined profile should emerge when aggregating an increasing number of load profiles.

In the papers a detailed validation is done against measured data for the 14 case-study households and against measured aggregate demand. It is found that all important features of measured demand are realistically reproduced by the model. These are:

- **End-use composition**, which depends on the overall occurrence of end-use activities in the synthetic activity patterns.

- **Diurnal and seasonal variations**, which are caused by the spread of activities in the synthetic activity patterns. Annual variations are mainly due to variations in daylight availability.

- **Short time-scale fluctuations**. These are caused by activity changes in the Markov-chain model between individual time steps. Estimates of transition probabilities from empirical TUD make sure that these are
highly realistic.

- **Diversity between households.** These are introduced mainly through different household sizes and variation in some parameters. The model captures important variation even in the small set of 14 measured households.

- **Load coincidence.** This depends on the spread of activities in the synthetic activity patterns and is highly realistic.

An example of a synthetically generated activity pattern is shown in Figure 4.4, in this case an occupancy pattern. The figure shows the number of people at home over a few simulated days, for 4 and 80 persons, respectively, and compares the synthetic patterns to empirical data from the TUD set. It is clear that the generated patterns closely resemble the empirical ones in terms of randomness and coincidence.

Figure 4.5 shows some resulting electricity demand patterns generated with the stochastic model. For one household, the generated profile is highly variable, showing intermittent peaks from different appliances, combined with smaller fluctuations on both fast and slow time scales. With an increasing number of households the aggregate output becomes smoother, reflecting random coincidence of the load profiles. The overall impression is that the patterns are highly realistic, which is confirmed by the more detailed validations in the appended papers.

### 4.3 Applications and Outlook

A major advantage of the model is that the variability and stochasticity are based on underlying activity patterns and not, for example, on observed variability in measured electricity use or other end-use data. This means that the model is not restricted to one type of end-use modelling but, on the contrary, that multiple end-uses can be modelled in basically the same way from the same data. This, in effect, has the advantage that correlations and restrictions between different end-uses are preserved, which would not be the case if data series were collected from a number of separate sources. Some applications of the general model framework have been identified:

- **Utilisation of on-site renewable energy.** The hot-water part of the deterministic model has been used in studies of how the performance of domestic solar heating systems is influenced by the load profile [104]. Load matching and grid interaction studies for photovoltaic systems are part of this thesis and are summarised in the next section.
Figure 4.4: Examples of synthetic activity patterns for the activity 'being at home' on five consecutive weekdays generated with the stochastic model, compared to examples of empirical activity patterns. The latter data consist of samples of individuals’ daily activity patterns from the TUD set, ordered in sequence.

- Simulations of electricity distribution grids. Because of the stochastic model’s ability to reproduce realistic demand patterns for both individual and large numbers of households, incorporating the coincidence effect, it is ideal for detailed simulations of electricity distribution grids, where a large set of individual households are included. This application is described in Section 6.

- Time-use studies and visualisations. Time-use diaries are often applied to make respondents aware of their activities and habits. Visualising the activity sequences that a diary-writer is involved in can reveal activity patterns that otherwise would be invisible in the complexity of everyday life. In feedback concerning energy-related habits, the possibility to model energy use from recorded activities with a sufficient accuracy would improve the feedback, and reduce the need for monitoring energy use. A software for visualisation of activity patterns, VISUAL-TimePaCTS [105] is currently being upgraded to include an energy end-use calculation
Figure 4.5: Examples of load profiles generated with the stochastic model, spanning one week. The data were generated with appliance load parameters and Markov-chain transition probabilities for detached single-family buildings as defined in Paper III. The time resolution is one minute.

and visualisation module based on the deterministic approach [XV]. An example of how the visualisation is presented in the program is shown in Figure 4.6.

• Building energy simulations. The ability of the model to reproduce different demand patterns from the same TUD is an advantage in simulations of low-energy buildings, where thermal loads from presence, appliances, hot-water use, etc., contribute to the thermal performance and the design of installed heating power. An extension of the deterministic approach to thermal load modelling is presented, together with application examples, in [XI]. An example of a detailed daily distribution of thermal loads and building simulation results such as average indoor temperature is shown in Figure 4.7.
Some points are important for consideration in future research and model development. One is the question of which degree of detail is necessary in general and for different applications. With a sufficiently detailed TUD set, an almost unlimited degree of detail is possible in both deterministic and stochastic profiles. However, model complexity, possibilities of simplification, the time needed for the numerical computations, and the necessary time resolution have to be considered for each individual application. For the stochastic model in particular, differences in the computation time can be substantial depending on the time resolution and, even more so, on the number of activities included in the Markov-chain model. Another important consideration is that of efficient collection of updated and sufficiently detailed TUD. The TUD should ideally be representative of the studied population and recorded with a sufficient degree of detail in terms of activity categories. One possible way of collecting TUD is via handheld devices, possibly with automatic activity categorisation [XI].
Figure 4.7: Energy balance of a combined kitchen and livingroom zone in a building energy simulation of a passive house using thermal loads deterministically modelled from TUD for a 6-person household [XI].
5. Load Matching and Grid Interaction

This chapter summarises the analyses of load matching and grid interaction of on-site photovoltaic generation that are presented in detail in Papers IV–VI. The main aim is to determine how residential buildings with on-site PV generation typically interact with the distribution grid, which may have consequences for voltage management in the grid at high penetration levels and for the economy of PV systems. These detailed studies of how different end-users utilise their on-site generation by default also indicate which activities typically increase the on-site matching, and which the possibilities for improved matching are. Studies of individual households are combined with more general estimations of the flexibility in the demand and generation profiles in order to increase the knowledge of how different strategies to improve utilisation of electricity generated on-site can be applied and valued.

Section 5.1 presents some analyses of load matching in residential buildings and how it varies between households. Section 5.2 discusses how the load matching can be improved by different options. Section 5.3 shows which the economic consequences of a mismatch between demand and generation profiles are for a small-scale residential producer, depending on the system for crediting of on-site generation.

5.1 Load Matching and Variability

The reasons for studying the load matching capability of grid-connected photovoltaic systems have been mentioned briefly previously. Because of the variability in both load profiles and photovoltaic generation it is common, for systems providing to more than a small fraction of the annual demand, with a mismatch between on-site demand and supply. In general, a higher degree of matching decreases the effective load on a distribution grid, which lowers distributed volumes, counteracts voltage drops and decreases losses. With large amounts of distributed generation, the degree of load matching has impacts on the design and operation of distribution grids. For individual buildings with on-site generation, load matching determines how the building interacts with the distribution grid, which may have impacts on the value of the electricity generated on-site, if bought and sold electricity are valued differently. In cases when it is beneficial to primarily use the generated electricity within the building, the degree of matching determines the system size that is reasonable to
install. In this and subsequent sections the load matching and grid interaction of some typical Swedish single-family residential buildings with on-site PV generation are determined, using the models described in the previous chapters, combined with measured load data for a number of different Swedish households.

5.1.1 Load matching at high latitudes
As discussed previously, solar energy availability at high latitudes varies depending on the season, with most of the energy being available during summer. The domestic electricity demand is also seasonally dependent, however with most of the electricity demanded in winter. This is true both for buildings with electric heating (due to the increased need for heating during winters) and for buildings with only household electricity (due to the increased need for lighting during the dark winter season). This gives rise to a seasonal mismatch between the generation and demand profiles. However, there is also a diurnal variation combined with more random fluctuations, which causes a mismatch on shorter time scales. Depending on the size of the grid-connected PV system, different volumes will be delivered to and supplied by the distribution grid. The mismatch on a typical summer day with two different PV system sizes in a building with non-electric heating is shown in Figure 5.1.

![Figure 5.1: Example of load matching of two differently sized PV systems. The load profile, from one of the households in Figure 4.2, is typical for a Swedish single-family house and the PV system output is determined from irradiance data for Stockholm, Sweden, with the model described in Section 3.1. The upper graph shows the matching and the lower graph shows the grid interaction in the two cases.](image)

As indicated by the figure, systems that produce volumes that are comparable to the demand on a summer day are heavily mismatched to the load profile. For systems that produce annual volumes comparable to the annual demand, the mismatch is considerably worse. The total mismatch, integrated over the
whole year, can be visualised as in Figure 5.2. The figure shows how much of the electricity delivered from the grid to cover the demand can be saved by local supply of electricity. The curves show, from bottom to top, the savings if the balance is calculated on an hourly, monthly and an annual time scale, respectively. As can be seen, the savings on an hourly basis level out and when the production is equal to the annual demand the savings are only 35%. If the balance is determined on a monthly basis—as is the case with net metering—the saved (or credited) electricity is approximately twice as large, but when a monthly surplus starts to form the savings level out.

As long as a surplus is submitted for free to the grid or receives a very low credit, as currently is the case in Sweden, it is reasonable to adjust the system size so that there is no or a low risk for overproduction. The roman numerals in Figure 5.2 indicate which these system sizes are for balances determined on the different time scales considered. For reducing the hourly surplus, a system that covers less than 20% of the annual demand should be chosen. For reducing the monthly surplus, as one would do with monthly net metering, a system with a production amounting to 50% of the annual demand should be chosen. The calculations are described further in Paper VI, and are applied to some more types of buildings. For a building with an even worse seasonal mismatch, the demand coverage of a PV system designed to minimise the surplus is much smaller.

![Figure 5.2: Electricity demand met locally in a building by on-site generation for different system sizes, calculated with annually (upper), monthly (middle) and hourly (lower) resolved data. The building load is for a non-electric heated single-family house, modelled with the stochastic load model described in Section 4.2. Roman numerals indicate the system sizes for zero overproduction on the respective time scale.](image)
5.1.2 Activity patterns and variations

As was described in Chapter 4, the case study on 14 households [XIX] had revealed considerable differences between electricity end-users in terms of annual demand and end-use composition, differences that could be traced back to habits and daily activities. An interesting question is how these differences affect the matching analysis outlined above. In Paper V, differences in demand coverage of a few different simulated PV systems was determined with load matching analyses on some of the 10-minutely, end-use-specific, demand data from the case study. The investigated time period covered the months May through July, the period that is most critical for load matching, with the domestic demand being at its lowest and the PV generation at its highest. Load patterns were analysed and conclusions about the daily distribution of loads were drawn from interviews with the household members.

Figure 5.3 shows, contrary to the figure above, how much of the production is used to supply the local demand in the studied households. The main observation in the study, as indicated by the figure, is that daily profiles and the resulting degree of matching with on-site generation differ considerably, just like diversity was found in the aggregate demand of the studied households. As can be seen in the figure, the production of a 1 kW system can be completely absorbed by one household while 60% is delivered as a surplus to the grid in another. Table 5.1 shows the highest installed peak power that is allowed if 90% of the production is to be internally used within the household to save purchased electricity. This results in limited system sizes for most households. It is worth noting that production of "your own electricity" requires very small systems if the electricity is really going to be exclusively your own.

![Figure 5.3: The fraction of on-site PV generation covered by the load for different household load profiles and system sizes, as determined in Paper V for the period May–July. The households are the same as in Figure 4.2.](image)

Many households, but not all, have clear fluctuations in the average daily power demand profile that follow the average domestic demand curve. For
Table 5.1: PV system sizes for 90% internal use of the production as determined in Paper V over the period May through July.

<table>
<thead>
<tr>
<th>Household</th>
<th>Peak power [W]</th>
<th>Total generation [kWh]</th>
<th>Total load [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartments:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>200</td>
<td>56</td>
<td>326</td>
</tr>
<tr>
<td>F2</td>
<td>340</td>
<td>95</td>
<td>441</td>
</tr>
<tr>
<td>K3</td>
<td>200</td>
<td>56</td>
<td>454</td>
</tr>
<tr>
<td>L4</td>
<td>450</td>
<td>126</td>
<td>1046</td>
</tr>
<tr>
<td>Detached houses:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>850</td>
<td>387</td>
<td>2396</td>
</tr>
<tr>
<td>G3</td>
<td>430</td>
<td>196</td>
<td>1183</td>
</tr>
<tr>
<td>I3</td>
<td>1450</td>
<td>660</td>
<td>2105</td>
</tr>
</tbody>
</table>

a) The households are the same as in Figure 4.2.

example, the demand typically increases during the afternoon and peaks in the evening. Not surprisingly, these profiles and the differences in load matching between the studied households were found to depend strongly on the occupancy patterns. Working from home, teenagers coming home early from school to play with computers, as well as daytime washing, drying and cooking were all associated with a higher degree of PV utilisation. For example, in the household with the largest system size for 90% utilisation in Table 5.1, a man was working from home with a lot of computer servers that were running constantly.

An interesting observation is that in some cases washing and drying were occurring during daytime. As these activities are sometimes thought of as shiftable through demand side management [106], this high degree of default matching seems to put restrictions to such actions. To determine if this is true in general, and to practically study potential impacts of different options to increase load matching, studies on aggregate demand profiles have to be performed.

5.2 Improved Load Matching

If, for some of the reasons mentioned above, an increased degree of load matching is desirable, there are some possible actions that could be taken. The impacts of these have been estimated and are summarised below. However, it is not entirely obvious how a mismatch should be valued, and whether an increased local load matching is always beneficial from an overall systems perspective, which is discussed briefly.
5.2.1 Options for improvement

In Paper IV, the degree of matching of a simulated PV system output to an aggregate domestic demand profile obtained from the deterministic load model described in Paper I is calculated and the impacts of different options for increased matching are estimated. The main indicator of load matching is the solar fraction (see Equation 3.36). No absolute system or load sizes are studied. Instead, relative system size is defined by the array-to-load ratio (ALR), which is the ratio of nominal PV peak power to mean demand. Two ALRs of 2 and 8 were studied. Systems with the latter ALR yield an annual output roughly equal to the annual demand. The studied options are:

- **Photovoltaic array orientation.** This involves a non-linear optimisation (Equation 3.32) of the proportions of systems with different orientations to get an aggregate generation curve that maximises the solar fraction. In practice, the tilt $\beta$ and azimuth angle $\gamma$ are varied in the solar energy model, which affects the radiation components on the tilted plane (cf. Section 3.1).

- **Demand side management.** Different shiftable amounts of energy are identified from the end-use composition of the load profiles. The impact on the solar fraction of optimal shifting of these loads to match the PV generation profile is determined.

- **Energy storage.** A simple storage model is implemented to shift overproduced electricity to time periods with a net demand. The impact of different storage sizes on the solar fraction is investigated.

The optimisation procedure for the orientation option has a clear impact on the orientation of systems, as shown in Figure 5.4. An east-west oriented setup of systems is optimal for increasing the solar fraction at high overproduction levels. Still, as is concluded in the paper, the resulting impact on the solar fraction is small. Storage is in general the most effective option, but DSM appears to be a realistic alternative to storage at moderate overproduction levels. For a system with annual demand coverage (ALR 8) a theoretical perfect daily match between the production and the demand increases the solar fraction from 35% to 65%, which is the limiting improvement for actions limited to individual days. These levels of improvements can only be reached by storage, but with load shifting the solar fraction can reach 41–48%.

The most easily achievable improvement should be PV array orientation, although it is highly dependent on the mounting possibilities on the actual building. DSM, in terms of voluntary load shifting by residents, is also an achievable option although load shifting with more extensive impacts involves violation of normal everyday activity patterns. It should also be noted that lighting
makes up a major proportion of the demand and is not shiftable. Storage is still an expensive option that is not a realistic complement to grid-connected PV systems at present. Thus, a general conclusion is that there is some theoretical potential for increased load matching, but that there are a number of practical obstacles in the way to realising it.

![Figure 5.4](image-url)

**Figure 5.4:** Optimal relative distributions of PV systems on different array orientations for maximization of annual (■) and summer (□) solar fraction at ALRs 2 and 8 in detached houses, from Paper IV. Numbers indicate the proportion of systems with the orientation in question. The contour curves indicate annual production relative to the production at optimal orientation with 5% steps, starting from 95%.

### 5.2.2 Valuing increased load matching

Although there are theoretical possibilities to increase the load matching and decrease the grid interaction of on-site generation, which can be motivated in some cases, it is not clear if it is always better from an overall systems perspective. One way to analyse the value of the mismatch is to correlate it to the demand on the electricity market. This can be done by simply calculating the hour-by-hour market value of the surplus generation and the net demand, respectively. The result of such a calculation for a detached single-family house modelled with the stochastic demand model and a PV system that covers the demand on an annual basis is shown in Figure 5.5. The figure indicates that the surplus is mostly valued higher than the net demand on the Nordic electricity spot market, and always higher on the German EEX market.

This indicates that, since the surplus generally assumes a higher value, there is a higher need for electricity in the system when the PV electricity is generated than when the building is supplied by the grid. Thus, from a systems perspective, it does not seem to be motivated to shift the production to match the local demand, but rather to distribute it to the rest of the system where it is needed. This is of course a marginal effect that will diminish with the penetration level of solar power on the market, but it is worth noting that the
5.3 Implications for the On-Site Production Value

Although the price fluctuations on the electricity market appear to favour solar electricity, this is not what a small-scale producer experiences. Purchased electricity is always more expensive than the spot market price because of energy taxes, value-added taxes, grid fees, etc. Therefore, without production credits given indirectly through net metering, or directly as feed-in tariffs, saved electricity or, analogously, locally generated electricity replacing purchased
electricity, is always worth more than electricity sold to the spot market price. Without credits, the degree of load matching determines the value of the generated electricity.

The decisive impact that the mismatch has on the production value does not seem to be entirely realised or given attention, and therefore a number of detailed load matching analyses were carried out in a project connected to the Swedish Energy Markets Inspectorate’s inquiry on the consequences of net metering. Some results are presented in Paper VI. Just like the saved electricity in Figure 5.2, the production value is a function of the system size. Figure 5.6 shows the resulting production value of on-site generation at the building studied previously, when assuming different alternatives for metering and debiting. The reason for the differences is that saved or credited electricity assumes the value of purchased electricity (125 EUR/MWh) while sold electricity assumes the market value (50 EUR/MWh). For system sizes where a surplus starts to form over the billing period, the value drops off with increasing system size, either towards zero or towards the selling price. The impact on system size in Figure 5.2 is seen more clearly here, namely that monthly and annual net metering alternatives increase the system size for which the production value stays at the buying price.

![Figure 5.6](image-url)  

*Figure 5.6: Production value of on-site generation for different system sizes, calculated for four different metering and debiting alternatives: billing of net load only (A), hourly selling of surplus (B), monthly net metering (C) and annual net metering (D). The building load is the same as in Figure 5.2. Roman numerals I–III indicate the system sizes for zero overproduction on the respective time scale, while IV and V indicate the system sizes for which the value of hourly sold electricity is equal to that obtained with monthly and annual net metering, respectively.*

The conclusions of these load matching studies are that net metering has a considerable impact not only on the production value of a given grid-connected PV system, but also on the system size that can be installed.
while keeping the production value at a maximum. For the typical household in Figure 5.6 the PV system that can be installed without producing any surplus would be sized to produce and save around 15% of the annual demand without net metering. With monthly and annual net metering the figures are 50% and 100%, respectively. For the typical PV system in the calculations this corresponds approximately to 5, 20 and 40 m$^2$ of the roof area. The form of crediting for on-site generation thus limits the utilisation of roof and facade areas otherwise available for mounting of PV systems.

5.4 Discussion

The studies have shown that the default degree of load matching varies considerably between end-users, if equipped with the same PV system. In general, though, there is a mismatch already for systems of a few 100 W$_p$, which limits the system size considerably if surplus generation is to be minimised. This mismatch can be improved in various ways. Load management, where loads are shifted to match a surplus production, seems to have a large potential, depending on course on which loads are possible to shift and with which flexibility. Not so surprisingly, the analyses of the case-study households showed that a high degree of matching resulted from daytime occupancy and activities such as cooking. However, loads that are sometimes considered shiftable, such as washing and dishwashing, often seem to match the PV generation by default. In general, the potential for improved load matching is restricted by the end-user’s availability and the fraction of shiftable loads already matching the PV profile.

The incentives for a small-scale producer to improve on-site matching or to limit the system size to avoid producing a surplus, depend on the value of sold electricity as compared to saved electricity. One way to deal with the mismatch is therefore to receive credits for surplus electricity, for example through net metering. Because of the default mismatch for many small-scale producers, net metering has a considerable impact, mainly because it eliminates the diurnal mismatch.

The value of the mismatch on a higher power system level has been touched on briefly. The next chapter will go into more detail on these questions and evaluate the impacts of a large-scale introduction of distributed generation on distribution grids and power systems.
6. Impacts on Power System Balance and Operation

This chapter presents the main results from the studies made on power system impacts in Papers VII–X. The aim with these studies was to determine the consequences of a large-scale introduction of PV-DG in distribution grids and in the national power system. Section 6.1 summarises the simulation studies of some Swedish distribution grids with high penetration levels of PV-DG. Section 6.2 presents a scenario for building-mounted PV and how it is used to study the characteristics and impacts of large-scale solar power, in combination with widespread wind power generation, on the Swedish power system.

6.1 Voltage Management in Distribution Grids

As discussed in previous chapters, massive introduction of PV-DG in distribution grids affects the voltage profile along distribution feeders, which may have impacts on voltage management and design of distribution grids. To make a detailed and realistic case study of the impact of distributed photovoltaics on distribution grids, three existing LV grids from the Uppsala region in Sweden were modelled and simulated. Detailed results are presented in Paper VIII. A summary of the most important considerations and results is given here.

6.1.1 Methodological considerations

Studies of power flow in distribution grids require a choice on the degree of detail for the studied load data in terms of end-use composition and diversity among individual households. In distribution grids, diversity and variability over time are important for realistically reproducing grid voltages. Aggregate profiles for groups of households could be used in larger grids where parts of the grid might have to be reduced to single nodes (cf. Paatero and Lund [55]). For large aggregates of households, random coincidence of loads levels out the aggregate demand, so that randomness in the load profiles can be neglected. However, in low-voltage grids with fewer customers, individual end-user profiles, as well as a realistic reproduction of the random coincidence of these profiles, are important. The stochastic load model described in Section 4.2 meets these requirements.
For PV generation, some coincident smoothing of aggregate profiles also takes place, due to differences in orientation, shading and cloud movements (see Section 6.2.2). Nonetheless, the coincident behaviour of PV generation profiles is in general much less pronounced than that of demand profiles. PV systems within a confined area will experience similar or identical meteorological conditions and identical outputs can thus be assumed. The annual and diurnal shape of the generation profile can be altered by PV panel orientation and thus an aggregate profile for differently oriented systems will have a different appearance than a curve for identically oriented systems; however, this cannot be expected to have an impact on shorter time-scale variations.

The choice of time resolution for the load and generation data used for the analyses is another important consideration, since power-flow simulations require a substantial amount of data processing. Although the stochastic load models can operate on an arbitrary time resolution, at least down to one minute, it is important to determine the loss of precision from time averaging to avoid unnecessary complexity. There seems to be a trend in international research towards more high-resolved modelling. As already mentioned, Thomson and Infield [56] performed high-resolution simulations on a 1-minute time scale. Detailed statistical studies of solar irradiation [70] and PV generation and demand [71] also suggest that important short time-scale fluctuations (on 1-minute or 10-minute time scales) may be overlooked if data are averaged over longer time intervals (typically hourly intervals).

An analysis of time averaging was performed in Paper VII to check if these suggestions motivate a high time resolution. The paper utilises measured demand and PV generation modelled from measured irradiance to study the impact of time averaging on data statistics, load matching and simulated voltage levels along an LV feeder. Differences between 10-minutely and hourly averages were determined over a period of four consecutive summer weeks.

It was found that although the impact on individual PV and demand data, in particular the latter, are sometimes considerable, the resulting duration curves for simulated grid voltages proved robust towards time averaging. This suggests that to determine probability distributions for different voltage levels, a higher time resolution than hourly is not needed. It is important to note that time averaging in general has a smaller impact on the PV system output than on the demand. The maximum PV power in every time step is also possible to predict very accurately, in contrast to the demand, defined as it is by the sun’s position in the sky and the orientation of the PV panels, and because the output is constrained by the peak power of the system. Any fluctuation in the PV output is a decrease in generation from this clearly defined generation profile.
6.1.2 Simulation results

The models described in previous chapters were combined in a complete framework to generate the necessary input data for the grid simulations and solve the power flow problem. A flowchart of the simulation procedure is shown in Figure 6.1. Load profiles (active and reactive power) are constructed with the stochastic load model and PV system outputs are generated from the solar energy models. For each load bus in the grid, representing an end-user, a set of profiles are added, following the previous outline in Figure 3.5. The voltages at every bus in the grid are then determined by solving the power flow equations using Newton’s method as described in Section 3.3.

Figure 6.1: Flowchart showing the simulation procedure in the distribution grid simulations. From Paper VIII.

Three grids were studied: two grids in an urban setting—one designed for district-heated buildings and one for buildings with direct electric heating—and one in a rural area. All grids are simulated with the same type of residential load profiles generated with the stochastic load model described in Paper III. The simulation results show that all studied LV grids can handle PV-DG up to the highest studied penetration level of 5 kW_p per household. With the reported capacities of the network cables and assuming 800 kVA distribution transformers, the power flows in the grid are always below capacity. All voltage variations stay within ±10% of nominal voltage in all studied grids and with all system sizes. With a net zero energy building scenario, volt-
ages above the stricter $\pm 5\%$ limit appear in the grid in the district-heated area, however with a low overall probability.

Naturally, the LV grid in the district-heated area showed the largest voltage variations. No substantial variations were found in the rural LV grid, which is rather small with few connected customers. In this case, the voltage variations would probably be higher if an overlying MV grid had been included. The impacts of the three main penetration level scenarios on the cumulative probability for end-user voltages are shown in Figure 6.2. There is a small overall shift to the right in the $1\,\text{kW}_p$ PV case. This indicates that there is a general mitigation of voltage drop along feeders due to PV-DG. At higher penetration levels, there is no further improvement of below-nominal voltages, but mainly an increased probability for voltage levels above nominal voltage.

![Figure 6.2: Cumulative probability distributions for end-user voltages in the LV grid in the district-heated area, calculated over the whole year and all end-users. The curves relate to different PV penetration levels (system size per household) as indicated. From Paper VIII.](image)

The $1\,\text{kW}_p$ level is most beneficial from the grid point-of-view. In this case the on-site generation decreases local demand, counteracts voltage drops and decreases losses. Only a small unmatched fraction of the total generation is exported from the LV grid with reverse power flow through the substation transformer. With increasing penetration levels, additional demand coverage is small and there is mainly an increase of reverse power flow.

The major difference compared to the original scenario is the pronounced seasonal variations in the grid voltages. This is shown in Figure 6.3. Apparently, the worst voltage drops in the grid are not mitigated by the PV-DG. There is an improvement of the summer voltage drops, but at the same time the highest voltage levels are increased heavily in the highest penetration level scenarios. Note that the highest peak voltage appears in spring because of the orientation of the system as mentioned in Section 2.4.1.
6.1.3 Comparison to previous studies

The obtained results differ somewhat from the already mentioned conclusions of Carlstedt et al. [57]. Since that report is the only other publication on general systems questions for PV-DG in Sweden, a comparison with its conclusions is motivated.

In the analysis that the report is based on, a minimum of power flow from and into individual end-user nodes with connected PV-DG units was found for 5 kW systems with a stochastic analysis. With the analysis in Paper VIII, this minimum occurs for 1 kW systems. This is more in line with results in international research and is highly dependent on the applied load model. The optimal PV-DG rating reported in Carlstedt et al. is two times higher than the maximum demand of individual end-users, while in Paper VIII the optimal rating is much smaller than the maximum demand in individual households and about equal to the maximum demand in the average profile calculated over all households.

The results in Carlstedt et al. are based on the national Swedish demand and not, as in Paper VIII, the specific domestic demand, which is much less correlated to the PV production profile. Furthermore, the stochastic approach underlying the results in Carlstedt et al. does not appear to take into account the negative seasonal and diurnal fluctuations that still do exist. Instead, randomly generated production and load data seem to be sampled independently from distributions determined from whole-year data series.

Figure 6.3: Seasonal variations in the voltage distribution of the LV grid in the studied district-heated area. From Paper VIII.
With the relevant correlations taken into account, as is done in the models described in previous chapters and the analysis in Paper VIII, there is a clear asymmetry in the effects of PV-DG on the cumulative probability distribution for the end-user voltages (cf. Figure 6.2). In the corresponding figure in Carlstedt et al. there seems to be a uniform increase of the probability for all voltage levels. This overestimates the benefits of PV and is a typical effect of independent sampling of production and demand, as the impact on PV-DG on each voltage level will be equal.

Finally, as discussed in Paper VIII, it is important to point out that the limit to the penetration level of PV-DG is not equal to the penetration level that minimises the exchange with the LV grid for individual households. The decisive limiting factors are a combination of grid topology, transformer ratings and voltage control. As shown in Paper VIII the studied LV grids in themselves can manage large amounts of PV, above the optimal ratings for minimum grid interaction in individual households. However, overall feasibility of PV-DG as compared to centralised generation must take into account the whole transmission and distribution chain, which requires wider system delimitations than in both Carlstedt et al. and Paper VIII. In any case, statements about general limits for PV-DG in LV grids should be avoided, in particular in relation to peak demand.

6.2 Impacts of Large-Scale Solar Power

Although the main focus of the thesis has been on rather local power system questions such as load matching and grid interaction of individual or groups of buildings with on-site generation, and grid impacts as presented above, an important question is what the implications are for the balance and operation of the power system on a national scale when large amounts of distributed photovoltaics are introduced. This section summarises the analyses presented in Papers IX and X, where some characteristics and impacts of large-scale solar power are studied.

6.2.1 A scenario for building-mounted PV in Sweden

As reported in Paper IX, a database with hourly data series of modelled power output from building-mounted PV systems was created. The aim was to obtain data for a future scenario of large-scale solar power generation that can be used for different purposes. One application is estimations of the potential of building-mounted PV, nationally and regionally. Another is to study hourly variations, random coincidence and smoothing effects from geographical dispersion with empirical data. The database can also be combined with data for wind power generation for studies of correlations and be used as input to system simulations with large amounts of PV generation.
The data underlying the simulations are measurements of solar irradiation from the Swedish Meteorological and Hydrological Institute (SMHI), collected at twelve locations in Sweden since 1983 [107]. Irradiation components and ambient temperature from nearby stations for a subperiod of eight years, 1992–1999, were selected. The model described in Section 3.1 was applied to calculate incident radiation on differently oriented areas and simulate PV systems. Figure 6.4 shows annual global irradiation at these stations, as a mean value over the studied eight years, for some differently oriented surfaces. It should be noted that there is no consistent decrease in energy collection with the latitude for optimally tilted systems. The availability of solar energy appears to depend more on local geographical and weather conditions.

Figure 6.4: Average annual solar radiation on the horizontal plane measured at the twelve radiation stations in Sweden, 1992-1999, and calculated radiation on tracking and optimally tilted surfaces for each location. The stations are sorted from left to right by increasing latitude.

A scenario for building-mounting of PV systems was constructed by determining available building areas, distributed on different geographical areas in Sweden. Starting from previously developed estimates of building areas on a national level in Sweden [108, 109], a distribution of differently oriented roof and facade areas on the different Swedish counties was obtained, using residential statistics and real estate tax assessments. The obtained per-county building areas were then distributed on the radiation stations, so that measurement data from each station were used as representative of the nearby counties. The result is a set of differently oriented and sized areas per station, for which production profiles were obtained with the solar energy models.

In total, a building surface area of 709 km$^2$ was available, but after reduction of surfaces that are unfavourably oriented a total area of 370 km$^2$ was
used in the calculations. Total PV electricity generation from these areas is on average 37 TWh per year between 1992 and 1999. The contribution of the different radiation stations, representing the surrounding built environment, is shown in Figure 6.5. Unsurprisingly, the largest contributions come from the densely populated areas in Eastern, Western and Southern Sweden. As shown in Paper IX, building-mounted PV needs a 25% larger solar cell area to produce the same electricity volumes as optimally oriented systems. Although resource-effective in the sense that it uses an existing infrastructure for mounting, building-mounting is less resource-effective in terms of solar cell material due to the non-optimal orientations.

Figure 6.5: Contribution of the built environment in different geographical regions of Sweden (represented by the respective radiation measurement station of the region) to the nation-wide PV generation from building-mounted systems in the studied scenario.

6.2.2 Variability and correlations with wind power

As discussed previously, large-scale solar power in Sweden will most likely be accompanied, or preceded, by a large-scale integration of wind power. Therefore, it is important to consider the interplay and correlations between solar and wind power on a national scale, if conclusions about a power system with large amounts of renewable generation are to be drawn. One interesting question is if a combination of different types of renewables will experience further smoothing from random coincidence, as is the case for geographically dispersed wind power. For these reasons, the solar power scenario described above was studied together with data from a large-scale wind power scenario, modelled from meteorological data from the same years, 1992-1999. The re-
results are presented in Paper IX but the most important observations are summarised here.

It was found, among other things, that solar power does experience a similar smoothing effect due to geographic dispersion as wind power. But whereas the correlation (Equation 3.38) between wind power plants decreases to nearly zero for sufficiently large distances, the correlation between the radiation profiles at maximum decreases to around 0.8. The weaker the correlation, the less likely the data series are to follow the same variations. A higher correlation thus tends to enhance variations while a low correlation tends to reduce variability. The higher correlation between the radiation data is of course because of the systematic seasonal and diurnal variability of solar irradiance. Figure 6.6 shows the distance dependence of the correlations between individual wind power and irradiance data series, respectively. Despite the preserved correlation for irradiance, fluctuations caused by local weather conditions randomly coincide to make the output smoother and more predictable, which is the critical property for the impacts on power system operation.

Figure 6.6: Correlation between individual hourly wind power and solar irradiance data series depending on the distance between the geographic locations. From Paper IX.

Figure 6.7: Duration graph for a combined solar and wind power profile, as compared to duration graphs for solar and wind power alone. The total electricity generated is on average 10 TWh per year. From Paper IX.

A further observation is the negative correlation between solar and wind power on all time scales. Monthly variability shows the clearest negative correlation. The overall negative correlation suggests that a combined output of
solar and wind power would be levelled out. As Figure 6.7 shows, the duration graph for a combined profile with 30% solar and 70% wind power (total generated electricity) is more evenly distributed than solar or wind power alone, or any other combination. This is also reflected in the standard deviation of the output, which has a minimum for this combination. However, as wind power fluctuates on a slower time scale than solar power, the hour-to-hour changes in the output are always higher with a higher proportion of solar power.

6.2.3 Impacts on the Swedish power system

The studied variability and the overall negative correlations between solar and wind power are important to take into account in power system simulations. In Paper X the Swedish power system is optimised under varying conditions with the energy system optimisation model MODEST (see Section 3.4). The model includes descriptions on an aggregated national level of the total power generation capacity as well as of the national district heating system. The energy flows from water resources and fuels, via power and heat production units, to electricity and district-heating demands are optimised to minimise the total system cost. A detailed description of the model, which is validated against reported key statistics for the year 2008 can be found in Paper X.

Solar and wind power data from the study presented in the previous section were used as input data and were added incrementally in two main scenarios. In the first scenario new solar and wind power capacity is added to the existing conventional capacity up to the most extreme case of 30 TWh of either power source. For wind power, this corresponds to the current planning goal for 2020 [110]. For solar power, it corresponds almost to the maximum production potential of building-mounted PV as described above. In the second scenario the same capacity is added but is accompanied by a phase-out of nuclear power by corresponding annual volumes.

The results for scenario 1 are shown in Figure 6.8. The main findings in this scenario are:

- There is an increased use of heat pumps for heat-only production in the district heating system. The heat pumps replace mainly other heat-only production fueled with biomass, but on some occasions in the most extreme case also combined heat and power plants (CHP) when there is an extreme overproduction of solar power.

- Water is spilled from the hydropower reserves in the most extreme case, as well as some of the solar and wind power generation. This is because the power demand, the transmission capacity and the heat pumps in the district heating system cannot absorb all of the power that is produced. Because of limitations of the storage capacity in the hydropower system, water has to be spilled if not utilised in the hydropower plants.
Figure 6.8: Example of power system impacts resulting from addition of large-scale solar and wind power generation to the present Swedish power system. Scenario A is the base case corresponding to today’s system. In scenario B, wind power of 30 TWh is added and solar power is incrementally increased from zero to 30 TWh in cases 1–4.
• Electricity exports increase, which helps reduce CO₂ emissions from coal-fired condensing plants in continental Europe.

It should be noted that in none of the studied cases could any definite limit to solar power integration be found, but, as seen from the results above, competition between different power and heat production plants may occur at extreme penetration levels, with spilled energy as a consequence. As discussed in Paper X, the model is based on the existing power and district heating system. In further research, other possible system changes besides integration of renewable power generation, should be considered, such as a large-scale introduction of electric vehicles, energy efficiency and increased transmission capacities.

6.3 Discussion
Are there any limits to massive integration of solar power? Although it is difficult to draw any general conclusions about integration of PV-DG in distribution grids from the case study presented in Paper VIII, some reflections can be made. The impact of PV-DG was not critical even at very high penetration levels, although 1 kWₚ systems were most beneficial for reduction of losses and improving voltage profiles. As already discussed, this differs from what has been previously found in Swedish studies. It is also a less restrictive result than those in some previous studies in other countries [56, 55]. More important, it is in line with what has been found from monitoring in areas with high-density PV-DG, where voltage rise does not set any definite limits [50, 51, 52].

In any case, the study also shows more general characteristics of PV-DG such as the dependence of grid voltage profiles on the seasonal and diurnal variability and the incremental changes in the probability distribution for the voltage with increasing penetration levels. In weaker grids the actual voltage variations would be higher but the relative impacts on the voltage profiles should be similar. If this would be the case, it would not necessarily set any technical limit to the integration of PV-DG because there are different measures that can be taken, such as improvement of cables, increased transformer capacity, changes to the tap-changing control, etc. These would be economical issues rather than technical.

Similarly, integration of solar power on a large scale does not, as seen, have any definite limitations. The energy spillage and use of heat pumps instead of existing CHP capacity should be seen as a matter of economic trade-offs, settled by the actors on the liberalised electricity market, rather than as unoptimal system solutions.
7. Summary of Conclusions

This chapter summarises the main conclusions of the appended papers, in relation to the aims of the thesis presented in Section 1.1.

Improved demand modelling (Papers I–III)

- The load modelling studies show that time-use data (TUD) can be used to provide a realistic basis for many different types of load modelling. Fairly simple conversions from TUD yield realistic energy load profiles and can be used for estimates of energy use from reported activities.

- Stochastic Markov-chain modelling of activity patterns from TUD can be used to generate highly realistic activity patterns, using a set of condensed data processed from larger TUD sets. This model, combined with appropriate functions for connecting energy end-uses to activities, generates high-resolution load profiles that reproduce important load characteristics such as diurnal and seasonal variations, short time-scale fluctuations and random load coincidence.

- Deterministic conversion from empirical TUD and construction of load profiles from stochastically generated activity sequences both have the advantage of allowing modelling of multiple end-uses, e.g. occupancy, lighting, appliances, hot water and heat loads, from the same data, thus preserving correlations between end-uses. Possible applications include studies of utilisation of on-site generation, distribution grid simulations, building energy simulations and energy-related time-use studies.

Load matching and grid interaction (Papers IV–VI)

- The load matching capability of on-site PV depends on the stochastic overlap with the end-user’s load profile. Empirical studies of electricity use in some individual Swedish households show that total electricity use, end-use composition and daily load profiles differ considerably between households, depending on family type, occupancy and daily
activities and habits. This variability is reflected in the load matching of PV systems. For example, the summertime production from a 1 kW\textsubscript{p} system may be completely absorbed in one household, while 60% of the production exceeds the load and is delivered to the grid in another.

- Default matching with the household electricity load profile is low. A system that minimises surplus generation is normally in the order of a few 100 W\textsubscript{p}. For systems that produce annual volumes comparable to the annual electricity demand (as in net zero energy buildings) the solar fraction is normally around 35%. Load matching can be improved by different options, e.g. storage, load management and PV array orientation. Storage is theoretically limited only by capacity and efficiency while DSM would at maximum increase the solar fraction to 48% and array orientation to 38%.

- Net metering reduces the effects of the mismatch on the production value of a PV system. Although the PV generation in general has a higher market value than the electricity demand, this is not experienced by a small-scale producer because the price for purchased electricity is always higher than the market value due to grid fees and taxes. Net metering reduces the mismatch by subtracting net production from net demand over a billing period and increases the system size for which all production saves purchased electricity. For a typical household without electric heating, a PV system that can be installed without producing any surplus would be sized to produce and save around 15% of the annual demand without net metering. With monthly and annual net metering the figures are 50% and 100%, respectively. For a typical PV system this corresponds approximately to 5, 20 and 40 m\textsuperscript{2} of roof area. Net metering would drastically increase the potential use of existing building areas for electricity production.

Power system impacts (Papers VII–X)

- Three existing Swedish LV grids were modelled and simulated in a case study. All grids appear to manage high penetration levels of PV-DG, up to the 5 kW\textsubscript{p} per household studied. For 5 kW\textsubscript{p} the design voltage limit of 1.05 p.u. is violated, however with a low overall probability. Grid interaction was minimised at a penetration level of 1 kW\textsubscript{p} per household, which reduced losses in the grid and improved the voltage profiles along distribution feeders. At penetration levels above 1 kW\textsubscript{p} per household, reverse flow through the distribution transformer increases and there is a higher probability for above-nominal voltages. These results are less restrictive than some results in previous research.
but correspond to findings from monitored areas with high-density PV-DG.

- A scenario for large-scale building-mounted solar power in Sweden was constructed based on available building areas and solar radiation data spanning 8 years (1992–1999) from a total of 11 meteorological stations in Sweden. Using all horizontal areas for mounting of optimally oriented systems and tilted areas facing ±90° of due south, 37 TWh would be produced at maximum, from a building area of 370 km². The regions surrounding the three largest cities of Stockholm, Gothenburg and Malmö would produce more than half of this volume, assuming a uniform spread of systems across the built environment. A 25% larger module area would be needed for building-mounted systems to produce the same volumes as optimally tilted systems.

- Studies of the variability of large-scale solar power from this scenario show a smoothing effect in the combined output of geographically dispersed systems. However, it is weaker than for wind power because of the systematic diurnal and seasonal variability. Large-scale national solar and wind power are negatively correlated on all time scales, from hourly to annual totals. A combination of 30% solar and 70% wind power (annual production) reduced the standard deviation of the combined output. However, hour-to-hour variability is always higher with a higher share of solar power.

- Impacts on the power system of a large-scale integration of solar power in combination with wind power were studied with the MODEST optimisation model. When solar and wind power are added to the existing system the main impacts are increasing electricity exports and heat pumps replacing heat-only production in the district heating system due to an increased electricity surplus. At extreme penetration levels, heat pumps replace combined heat and power (CHP) plants and both water in the hydropower system and solar and wind power have to be spilled occasionally. If combined with a simultaneous nuclear power phase-out the main impact is an increase in both exports and imports of electricity due to higher production variability.
8. Sammanfattning på svenska

Under de senaste tio åren har installerad effekt från solcellssystem (eng. photovoltaic systems) ökat kraftigt runtom i världen. I de länder som deltar i solcellssamarbetet inom International Energy Agency (IEA) har total installerad toppoeffekt ökat från under 1 GW till mer än 13 GW mellan 2000 och 2009. En majoritet av systemen är nätanslutna och många är installerade på byggnader i eldistributionsnät. Utvecklingen har varit beroende av de generösa stödsystem, framför allt inmatningstariffer (feed-in tariffs), som har införts, och fortsätter att införas, i många länder. De största marknaderna för solcellssystem har länge varit Tyskland, Japan och USA, men under de senaste åren har en kraftig ökning av installerad effekt skett även i andra länder, framför allt Spanien.


Den här avhandlingen handlar om möjligheterna för småskaliga solelproducenter att utnyttja egenproducerad solel, och om några av konsekvenserna av en storskalig utbyggnad av sådan distribuerad solelproduktion i Sverige. Några frågor som har ställts under genomförandet av forskningsprojektet gäller hur användningen av solel ser ut i typiska hushåll, hur utnyttjandegraden av egenproducerad solel varierar och vad det beror på, vad värdet på den producerade solelen är för en småskalig producent beroende på olika system för tillgodoräkande av överproduktion, hur distributionsnätens påverkas av en ökande mängd installationer, samt vilka följderna skulle kunna bli för det svenska kraftsystemet vid en verkligt storskalig utbyggnad.

Avhandlingen behandlar tre huvudsakliga områden:

1. **Förbättrad modellering av elanvändning i hushåll.**
   För att kunna studera hur väl ett solcellssystem täcker elanvändningen i hushåll, och för att kunna göra detaljerade simuleringar av distributionsnät med hög solandel, måste man ha tillgång till detaljerade data över elanvändning i hushåll och hur den varierar över tid. Som ett alternativ till att använda

2. **Studier av utnyttjandegrad och utbyte med elnätet.**

Ett solcellssystem producerar huvudsakligen el under sommarhalvåret och under dagtid. Eftersom elanvändningen i svenska hushåll i allmänhet är som lägst på sommaren och under dagen kommer ett solcellssystem att generera ett överskott, om det dimensioneras för att bidra med mer än en försumbar andel av elanvändningen sett över året. Utan någon form av stöd som ökar solelens produktionsvärde, till exempel inmatningstariffer eller nettodebitering, där produktionsöverskottet dras av från elanvändningen under en avräkningsperiod, kommer det alltid att vara fördelaktigt att använda den egna solelproduktionen för att ersätta köpt el och minimera överskottet. Syftet med studierna var att se hur utnyttjandegraden ser ut i olika hushåll, uppskatta hur den kan öka, och undersöka vilka de ekonomiska konsekvenserna är med och utan olika former av nettodebitering.

3. *Påverkan på kraftsystemet.*

Frågan om vilken påverkan en ökande mängd varierande produktion har på det svenska kraftsystemet är komplek och beror på många olika faktorer. I projektet studerades dels hur spänningsvariationerna i några verkliga distributionsnät påverkas av hög utbyggnadsgrad av distribuerad solelproduktion, dels konstruerades ett scenario för storskalig solelproduktion som användes för att studera samvariationen med vindkraft i stor skala, och för att bedöma effekterna på det svenska kraftsystemet på nationell nivå. I scenariot utnyttjas en stor del av tillgängliga tak- och fasadtytor i det svenska byggnadsbeståndet, vilket skulle ge en maximal solelproduktion på 37 TWh (givet en genomsnittlig verkningsgrad på 14% för solcellerna). Mer än hälften av produktionen skulle ske i storstadsregionerna.

De huvudsakliga slutsatserna från studierna är att lågspänningsnät i allmänhet verkar klara en hög penetrationsgrad av solel, vilket stämmer överens med observationer som har gjorts i de relativt få områden i världen som har en hög lokal utbyggnadsgrad. När det gäller samvariationen med vindkraft är storskalig sol- och vindkraft negativt korrelerade på alla tidsskalor, från timvisa till årsvisa variationer, men starkast på månadsbasis. Studierna visar vidare att en sammanlagd produktion av sol och vindkraft kan ge en jämnare fördelning av producerad effekt över året, men att variationer från timme till timme alltid är större med en större andel solkraft. I en optimeringsstudie visas att en överskottsproduktion av en hög andel sol- och vindkraft (upp till 30 TWh vardera) i det svenska kraftsystemet framför allt skulle öka exporter till utlandet, men även göra det lönsamt att tidvis ersätta bränslebaserad värme produktion och även kraftvärmeteråg i fjärrvärmenät med elvärmor, vilket skulle minska användningen av biobränsle. Vid en hög utbyggnadsgrad där produktionen inte ges avsättning spells vatten i vattenkraftsystemet. Studien har gjorts utifrån hur kraftsystemet ser ut idag. En omfattande utbyggnad av solel skulle rimligtvis åtföljas av andra förändringar i systemet, exempelvis en ökad exportkapacitet.

Sammantaget visar studierna att de största begränsningarna för solel i Sverige inte ligger i tillgången på solenergi eller i tekniska begränsningar i kraftsystemet, utan framför allt i svårigheten för egenproducert att tillgodoräkna sig överproduktion av el, vilket kraftigt begränsar storleken hos installerade system och ökar återbetalningstiden. För att öka incitamenten för att installera solelssystem som utnyttjar en större del av tillgängliga ytor i bebyggelsen krävs inte bara ett investeringsstöd utan även en stödform som gör att effekterna av den bristande matchningen mellan solelproduktion och elanvändning minimeras.
Lots of people deserve recognition for their contributions, in different ways, to the work presented in this thesis. Here we go:

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[50] PV-UPSCALE. Impact of photovoltaic generation on power quality in urban areas with high PV population—results from monitoring campaigns. WP4 - Deliverable 4.3, 2008.


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